RTMD

REAL-TIME MULTI-DIRECTIONAL SIMULATION

NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

NHERI Lehigh RTMD Experimental Facility

User's Guide

November 2, 2016

Preface

To help meet the grand challenge of community resilience to natural hazards, the Natural Hazards Engineering Research Infrastructure (NHERI) Lehigh Real-Time Multi-Directional (RTMD) Experimental Facility (EF) was funded by the National Science Foundation (NSF) to be a world-class, open-access facility that enables researchers to address key research questions associated with the challenge of community resilience. The Lehigh EF has a unique portfolio of equipment, instrumentation, infrastructure, testbeds, experimental simulation control protocols, and large-scale simulation and testing experience along with know-how that does not exist elsewhere in the United States. The unique strength of the Lehigh EF is accurate, large-scale, multi-degree-of-freedom and multi-directional simulations of the effects of natural hazard events on civil infrastructure systems (i.e., buildings, bridges, industrial facilities, etc.) with potential soil-foundation effects. The types of laboratory simulations and tests enabled by the Lehigh EF include: (1) hybrid simulation (HS) which combines large-scale physical models with computer-based numerical simulation models; (2) geographically distributed hybrid simulation (DHS) which is a HS with physical models and/or numerical simulation models located at different sites; (3) real-time hybrid earthquake simulation (RTHS) which is a HS conducted at the actual time scale of the physical models; (4) geographically distributed real-time hybrid earthquake simulation which combines DHS and RTHS; (5) dynamic testing (DT) which loads large-scale physical models at real-time scales through predefined load histories; and (6) quasi-static testing (QS) which loads large-scale physical models at slow rates through predefined load histories.

This User's Guide is intended to provide to the reader basic information about the NHERI Lehigh RTMD EF to enable visitors to get acquainted with the facility and to assist researchers in preparing proposals to use the facility. The information provided in this guide includes: information about the NHERI Lehigh RTMD EF and equipment, testing methodologies, telepresence, education and outreach, policies and procedures for using the facility and the organization of the NHERI Lehigh RTMD EF. In addition to the NHERI Lehigh RTMD EF, information about the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Facility and associated non-NHERI equipment and facilities available to researchers is provided. The NHERI Lehigh RTMD EF has an assortment of training materials, which along with the training workshop schedule, are summarized on the NHERI Lehigh RTMD EF web page (http://www.designsafe-ci.org). The reader is referred to this link for information on training.

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1 Facility Information

1.1 RTMD Overview

NHERI Lehigh's RTMD EF is located within the University’s ATLSS Engineering Research Center on Lehigh University's Mountaintop Campus in Bethlehem, Pennsylvania. The NHERI Lehigh RTMD EF allows for multi-directional real-time seismic testing, combined with real-time analytical simulations, to investigate the behavior of large-scale structural components, structural sub assemblages, and super assemblages (systems) subjected to dynamic loading from natural hazards, in particular seismic loading. This is achieved through the combined use of dynamic actuators, a reaction wall, and a strong floor. This facility is also designed to support the development of new hybrid testing methods for real-time multi-directional testing of large-scale structures, including multi-substructures, where the substructures involved are at different geographic locations connected by the Internet.

Figure 1-1 ATLSS Multi-directional reaction wall

The RTMD facility has the capabilities to perform real-time testing using the effective force method, pseudo-dynamic testing method, or the pseudo-dynamic hybrid testing method for the testing of large-scale structural components, structural subassemblages, and superassemblages under dynamic loading. The laboratory includes a strong floor that measures 31.1m x 15.2 m in plan, and reaction walls up to 15.2 m in height. Anchor points are spaced on a 1.5-m grid along the floor and walls. Each anchor point can resist 1.33 MN tension force and 2.22 MN shear force. Additional steel framing is used in combination with the strong floor and reaction walls to create a wide variety of test configurations. A 178-kN capacity overhead crane services the test area and an adjacent fabrication area. Additional smaller cranes with capacities of 45-kN and 27-kN also serve this area. The equipment portfolio and resources of the RTMD facility include:

- **Actuators** - five dynamic actuators, each ported for three servo-valves with stroke ranges of +/- 500 mm, and having the following maximum force capacity:

  - 3 actuators @ 1700 kN capacity at 20.7 MPa (3000 psi)
  - 2 actuators @ 2300 kN capacity at 20.7 MPa (3000 psi)
  - The maximum velocity that can be achieved by the actuators is 840 mm/sec (2300 kN actuators) and 1140 mm/sec (1700 kN actuators) when three servo-valves are placed on the actuators and the supply hydraulic pressure is 20.7 MPa (3000 psi). With a force on the actuator, the velocity capacity will be reduced. Shown below in Figure 1-2 is the force-velocity capacity relationship for each actuator, with the number of servo-valves on the actuator ranging from 1 to 3.

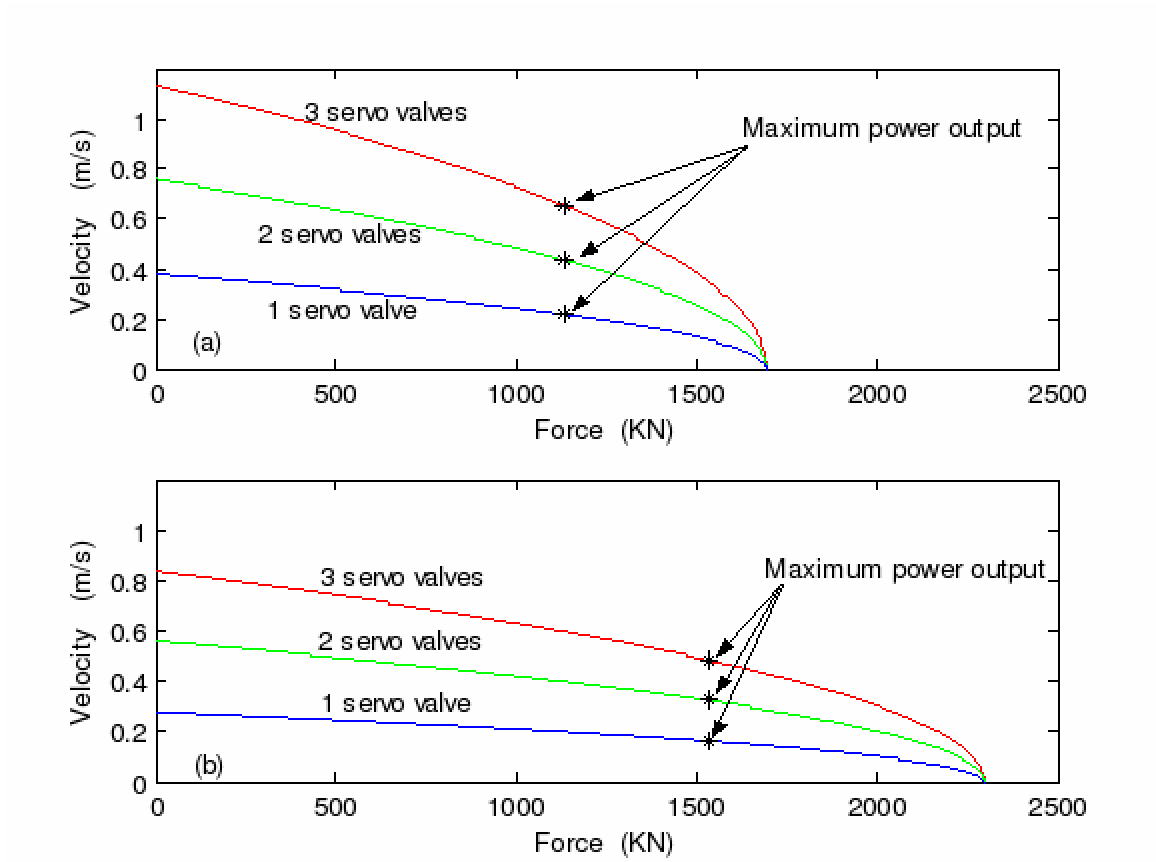

Figure 1-2 Hydraulic actuator power envelop for (a) 1700 kN actuators, and (b) 2300 kN actuators (20.7 MPa supply pressure)

- **Servo-valves** - ten three-stage, high flow-rate servo-valves rated at 1500 liters/min at 11 MPa (400 gpm at 1600 psi).

- **Hydraulic distribution lines and service manifolds** - low-pressure and high-pressure settings to operate at 20.7 MPa (3000 psi) with a maximum flow of 1500 liters/min (400 gpm). Surge tank and three banks of accumulators that enable strong ground motion effects to be sustained for up to 30 seconds. Each bank consists of twelve 114-liter (30 gallon) accumulators, to supply a total accumulated oil supply of 4090 liters (1080 gallons).

- **Accumulators** - 3028 liters (800 gallons) total capacity with a maximum operating pressure of 24 MPa (3500 psi). A hydraulic system connects the accumulators to the pressure line of a five pump 2250 liter/min (594 gpm) hydraulic system. The total hydraulic power supply therefore consists of the five pump system and the accumulators. Peak flow rates of 15,150 liter/min (4000 gpm) have been obtained using this hydraulic power supply, and enables typical strong ground motion effects to be sustained for up to 30 seconds.

- **Control Systems**
  - **Servotest Pulsar DCS** digital 8-channel 1024 Hz control system with each channel of the controller designed to follow an independent, random load, or displacement history. Five of the eight channels are operational for controlling the NHERI actuators.
  - **Wineman INERTIA** real-time, integrated, multi-loop control and data acquisition system for servo-hydraulic applications. The PXI/SCXI-based system supports control of ten servo values for multiple configuration of actuator load and displacement control along with 128 channels of data acquisition. INERTIA is a configurable test executive, which allows significant end user configuration.

- **Data Acquisition System** - high speed 304-channel (384 max) data acquisition system, capable of acquiring a single channel of data up to 1 million samples per second. Existing channel configuration limits to 10,000 samples per second. In conjunction with SCRAMNet synchronization, acquisition is limited to 4096 samples per second.
  - **Conventional sensors** - DC-LVDTs, temposonics, load cells, accelerometers and inclinometers.

- **Simulation System** - combination of a MATLAB host workstation and multiple target Simulink Real-Time Speedgoat[1] machines (formerly “xPC Target”). This applies the algorithms that generate commands for actuators and acts as supplemental data acquisition. Data channels from the control system(s) and data acquisition system are synchronized with the simulation data.

[1] https://www.speedgoat.ch/

- **Video System** - digital high quality video cameras, network video cameras, digital video server, data server, restricted access web server, and a public access web server. Digital video and data are provided by means of the video and telepresence servers. The digital video is acquired from pan-tilt-zoom web cameras and fixed web cameras. Six GoPro Hero cameras available for HD video and slow motion recording.
- **Risk Mitigation** – 32TB Dual Redundancy network file system for system and test data backups along with nightly offsite mirroring at Texas Advanced Computing Center.

1.2 ATLSS Overview

The ATLSS Engineering Research Center includes a multi-directional testing laboratory with a 12.1 m (39.7 ft) by 30.5 m (100.1 ft) strong floor and reaction walls up to 15.3 m (50.2 ft) in height along two full sides and parts of two others. The reaction wall and test floor have a 1.524 m (5.0 ft) square grid of high capacity anchor points which allow large-scale two-and three-dimensional test structures and test frames to be fastened to the wall and floor to facilitate multi-directional (multi-axis) loading.

The lab is equipped to generate multi-directional static and time-varying loads. The hydraulic power system consists of five pumps that deliver 2272 liters/min (600 gpm) at 24 MPa (3500 psi).

ATLSS has three main data acquisition systems (1 with 256 channels and 2 with 192 channels) for conditioning and acquiring data from experimental research. More than 200 channels of signal conditioners are available for use with these systems. Data acquisition systems for remote data logging are available for field tests. These systems are also used in the lab. The laboratory floor has been equipped with a switched gigabit network, providing network connections every 4.57 m (15.0 ft) along the reaction walls. Network connections in the laboratory currently connect to the main campus backbone by way of a switched fiber optic network.

Adjacent to the strong floor is a sizeable service area for specimen fabrication, preparation, instrumentation, and storage. The service area contains welding equipment, a large-bed drill press, a band saw, a grinder, and an array of hand tools.

The ATLSS multi-directional testing laboratory is served by a radio-controlled overhead traveling crane with a 178 kN main hoist and a 45 kN auxiliary hoist. Large overhead doors (6.1 m (20.0 ft) tall by 7.6 m (24.9 ft) wide) and large paved areas outside the lab provide easy access for tractor-trailer trucks delivering test specimens, equipment, materials, and supplies to the lab.

Within the Imbt Laboratories Building, the ATLSS Engineering Research Center operates a Mechanical Testing Laboratory, a Welding and Heat Treating Laboratory, and Metallography and Microscopy Laboratories. See Section 6 for details.

1.2.1 Facility Details

1.2.2 Reaction Wall Capacities

- Concrete Strength 7,500 psi floor and walls.

Table 1-1 Multi-directional reaction wall design capacity

Wall Height	Design Capacity (@base of wall)
(6.09m) 20ft	(2034 kN m) 1500ft-kips
(9.14m) 30ft	(3389 kN m) 2500ft-kips
(12.19m) 40ft	(6100 kN m) 4500ft-kips
(15.24m) 50ft	(6100 kN m) 4500ft-kips

1.2.3 Anchor Assembly Capacities Floor and Wall

- Shear (2224 kN) 500 kips
- Tension (1334 kN) 300 kips

1.2.4 Other Available Equipment

Table 1-2 ATLSS Existing Major Equipment

Equipment	Year Acquired
Multi-Directional Reaction Wall System	
15.2m to 6.1m tall L-shaped reaction wall	1989
30.5m x 12.2m strong test floor	1989
Hydraulic Equipment	
20.7 MPa (3000psi) Hydraulic power system with 2270 liters/min	1988,1992**
Central hydraulic distribution system	1988,1992**
6-Vickers Service hydraulic manifolds (1500 liters/min)	n/a
Hydraulic Loading Equipment	
Satec 2670 kN universal test machine	1992
MTS 245 kN fatigue test machine	1992
Hydraulic Actuators	
3-2680kN Hanna, +-750 mm stroke, 20mm/sec max. velocity*	1997
2-2050kN Hanna, +-480 mm stroke, 25mm/sec max. velocity*	1988
4-1500kN Hanna, +-480 mm stroke, 35mm/sec max. velocity*	1988
2-150kN Hanna, +-125 mm stroke, 35mm/sec max. velocity*	1988
2-1050kN Hanna +-125 mm stroke, 50mm/sec max. velocity*	1988
2-607kN Hanna, +-300 mm stroke, 80mm/sec max. velocity*	1988
8-580kN Hanna, +-125 mm stroke, 60mm/sec max. velocity*	1992

2-1000kN Hanna, +-125 mm stroke, 35mm/sec max. velocity*	1992
2-130kN T/J, +-125 mm stroke, 320mm/sec max. velocity*	1995, 1998
Controllers	
4-Vickers controller systems	1994
1-Portable Vickers Controller System	1994
2-MTS 458 Controllers	1985
Data Acquisition Systems	
1-OPTIM Megadeck 2300 (256 channels)	1987
2-Keithley Instruments DAS1802HC (192 channels)	1995, 2001
200 channels of signal conditioners	1986, 2001
Overhead Crane Systems	
180 kN radio controlled	1989
90 kN radio controlled	1989
Special Equipment	
V-Notch Charpy testing machine	1992
SEM and Light Microscopy equipment	1992
Trilion Aramis 3D Image Correlation System	2007
Instrumentation: Sensors	
Displacement transducers: ranging from +/-6.4mm (LVDTs) to 1524mm (linear potentiometers). All transducers are calibrated to within +/-1% accuracy, with the LVDTs calibrated to within +/- 0.1%	n/a
Inclinometers: ranging up to +/-20 degrees with 1% accuracy	n/a
Strain gages: 150ohms to 350ohms; signal condition enables various ranges of accuracy to be achieved	n/a
Load cells: each hydraulic actuator (noted above) is equipped with a load cell. All load cells are calibrated to within +/-0.1% accuracy	n/a

Note: Data based on standard 150 liters/min servo-valve.

**hydraulic system upgraded in 1992

1.2.5 Schematics of ATLSS Multi-Directional Reaction Wall and Strong Floor

Shown below are schematics of the multi-directional reaction wall and strong floor, which includes dimensions of the wall heights and length, and locations of the tie down points.

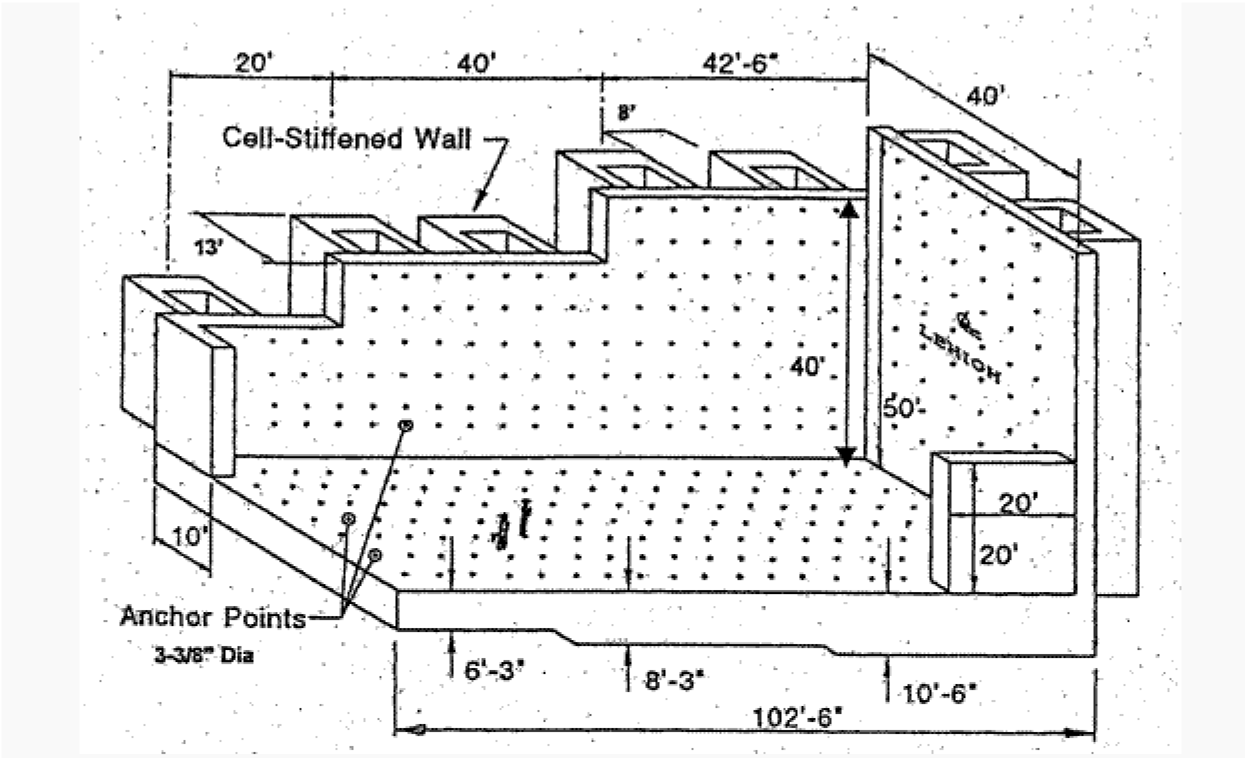

Figure 1-3 Multi-directional reaction wall and strong floor - isometric view

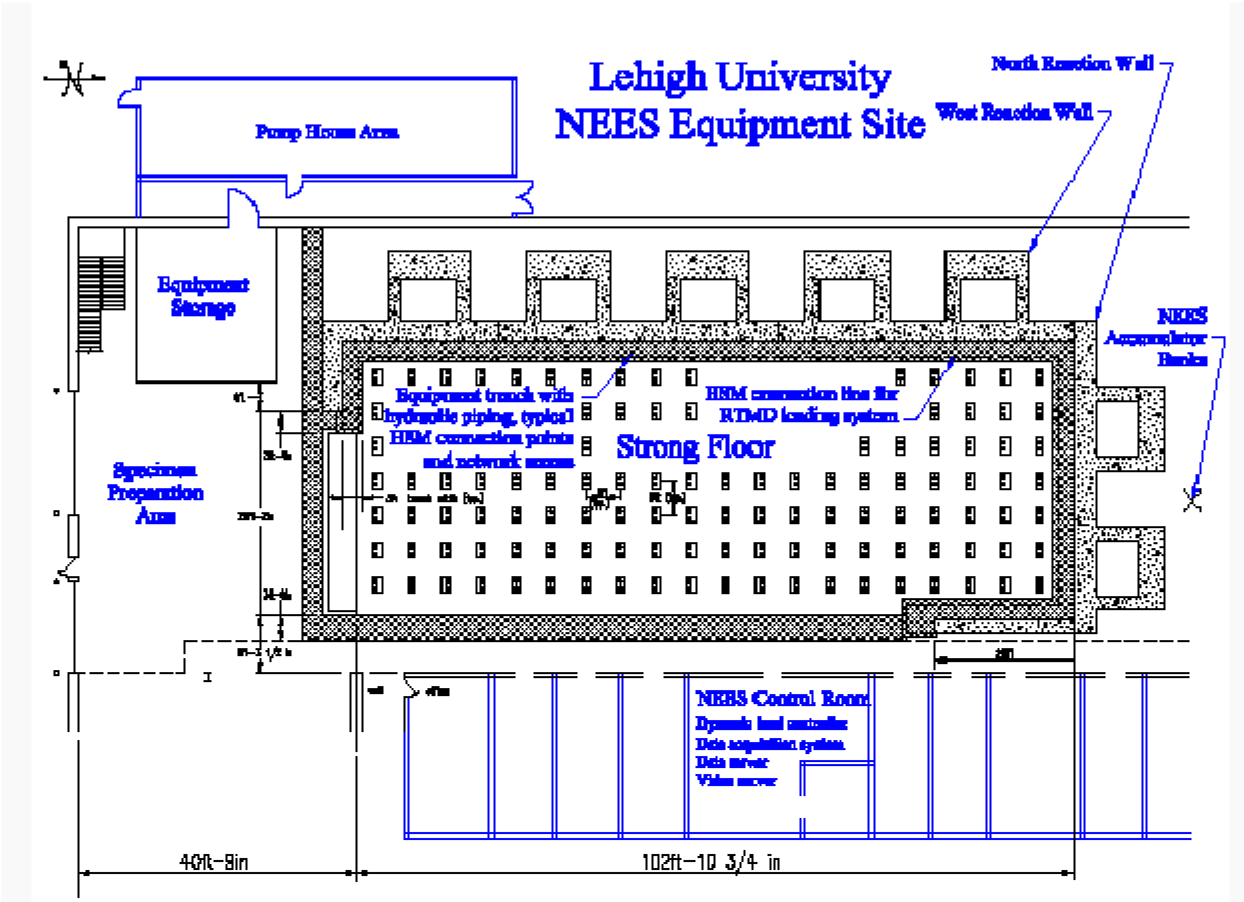

Figure 1-4 Floor Plan of RTMD Facility

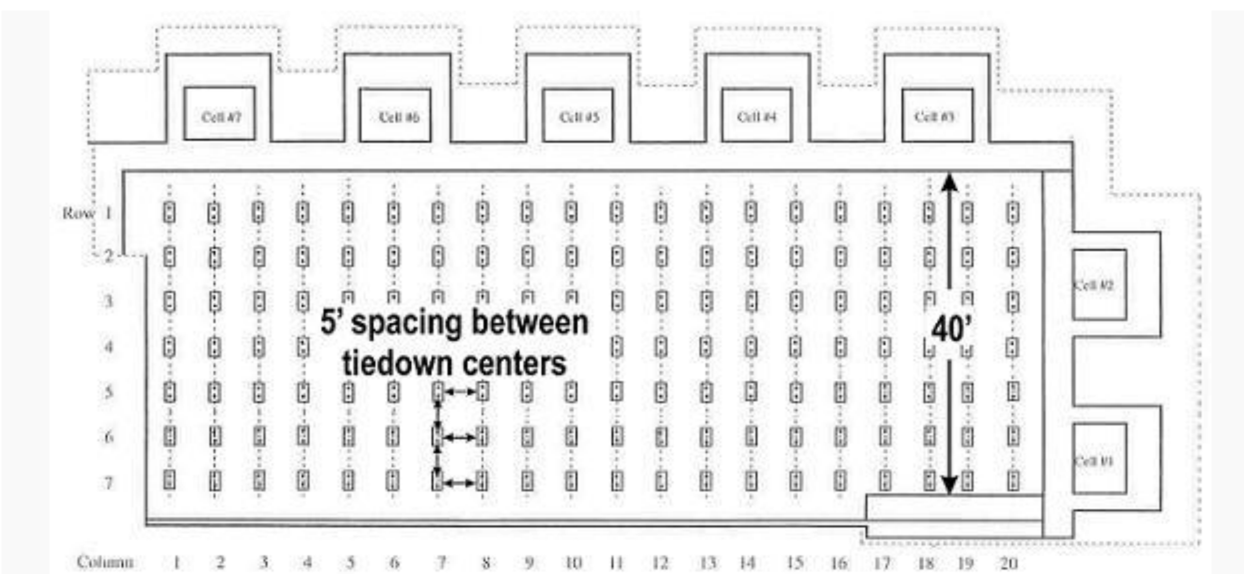

Figure 1-5 Floor Plan of Strong Floor

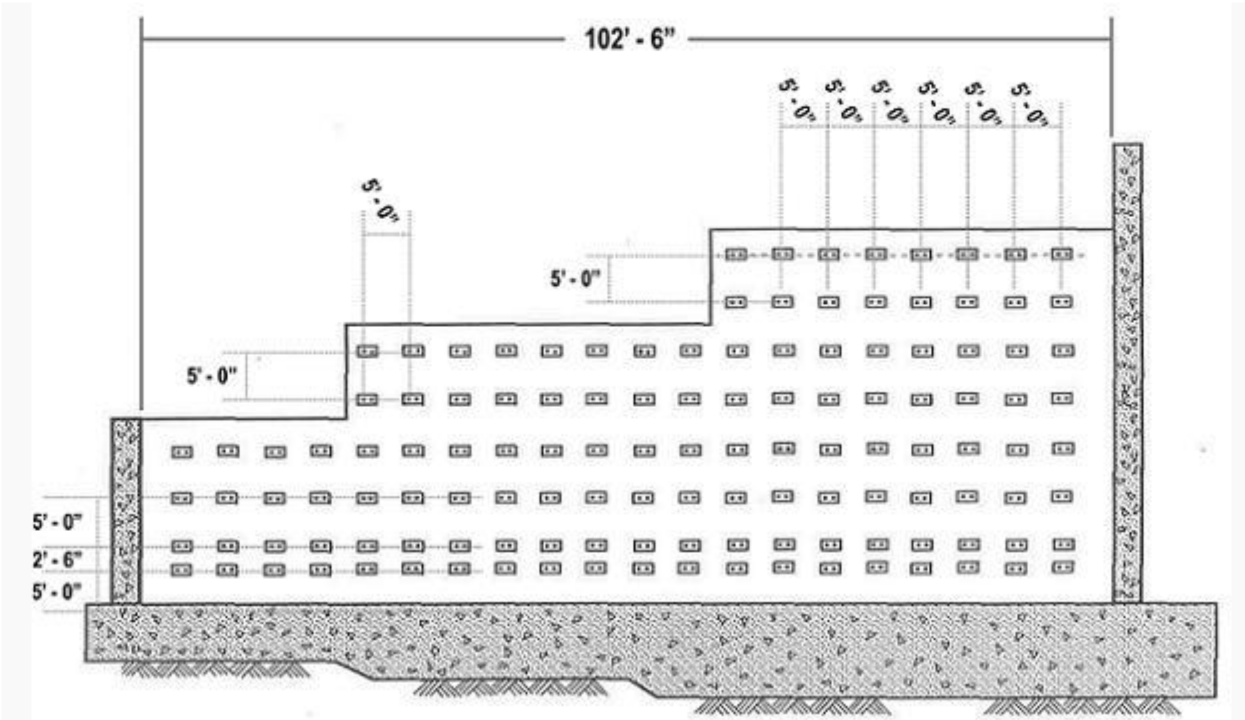

Figure 1-6 ATLSS West Reaction Wall Elevation

1.3 RTMD Equipment Specifications

1.3.1 Hydraulic Supply System

The hydraulic supply system consists of 5 pumps, 450 liters/min (118.9 gallons/min) each and 16 piston accumulators, 190 liters (50.2 gallons) each connected to 9 Nitrogen gas bottles, 1325 liters (850.2 gallons) each. This configuration enables a typical earthquake to be simulated on a 4-floor one-half scale frame structure in real time for 30 seconds with the supply pressure maintained within 20.7~24.1 MPa. The accumulators and gas bottles are expandable. If there is a higher flow rate demand, more gas bottles and accumulators may be purchased and configured.

1.3.1.1 Pumps

There are 5 variable axial piston pumps. Each of them provides a flow rate of 450 liters/min (120 gpm). The pump pressure limits are set at 24 MPa (3500 psi). When the supply pressure reaches this limit, the pump outputs zero flow. Table 1-3 lists the pump system specification.

Table 1-3 Pump system specifications

Pump Flow Capacity	2,250 liters/min (total)
Pump Pressure	24.1 MPa
Continuous Power Rating	1,800 kW (input power capacity)
Continuous Power Output	912.2 KW (output power)
Fluid Viscosity @ 40C	46 cSt (mm2/s)
Fluid Density @ 15C	0.87 Kg/m3

1.3.1.2 Accumulators

There are 16 piston accumulators connected to 9 gas bottles. Each piston provides 190 liters (50 gallons) of flow and each gas bottle combines 1325 liters (350 gallons) of Nitrogen. The hydraulic pressure can be charged to 24 MPa (3500 psi) by the pumps. When fully discharged, the accumulators still maintain hydraulic pressure above 20.7 MPa (3000 psi) if the subsequent flow rate demand can be sustained by the 5 pumps. The specification for the accumulator system is listed in Table 1-4.

Table 1-4 Accumulator system specifications

Accumulator Gas Volume	11,923 liters
Accumulator Oil Volume	3,028 liters
Peak Flow Capacity	> 13,605 liters/min
Normal Operation Pressure	20.7~24.1 MPa
Peak Power Capacity	> 4,693.7 KW

1.3.2 Actuators

There are 5 hydraulic actuators. Two of them have a maximum load capacity of ±2300KN at 20.7 MPa (517 kip at 3000 psi). The remaining three actuators have a maximum load capacity ±1700KN at 20.7 MPa (382 kip at 3000 psi). However, the external physical dimension and appearance for these five actuators are all same. The nominal supply pressure for the actuators is 20.7 MPa (3000 psi) but a pressure of 24.1 MPa (3500 psi) can also be supplied. Table 1-5 lists the hydraulic actuator specification. Detailed drawings of the Actuator can be found in Table 1-6.

Table 1-5 Hydraulic actuator specifications

Actuator Type	**200-100-1700**	**200-1000-1250**
Quantity	2	3
Load Regulation Accuracy	0.2% FS (but no higher than ±0.23KN)	0.2% FS (but no higher than ±0.17KN)
Load Tracking Dynamic Bandwidth	> 10Hz	> 10Hz
Displacement Regulation Accuracy (Static)	0.2% FS (but no higher than ±0.1mm)	0.2% FS (but no higher than ±0.1mm)

Displacement Tracking Dynamic Bandwidth	> 10Hz	> 10Hz
Load Capacity	±2300KN @ 20.7MPa	±1700KN @ 20.7MPa
Speed Capacity	0.84m/s (33in/s)	1.14m/s(45in/s)
Piston Diameter	424mm	378mm
Piston Rod Diameter	200mm	200mm
Stroke	±500 mm	±500 mm
Total Chamber Volume	114 liters	84 liters
Chamber Internal Leakage	0.15 liters/min/bar	0.15 liters/min/bar
Chamber External Leakage	0.01 liters/min/bar	0.01 liters/min/bar
Moving Part Mass (Piston & Rod Assembly)	950Kg (approximately)	900Kg (approximately)
Actuator Weight	6100Kg	6120Kg
Actuator Dimension (Clevis End to Clevis End at mid stroke)	5.355m x 1.25m x 1.35m (length x width x height)	5.355m x 1.25m x 1.35m (length x width x height)
Actuator Dimension (Clevis Pin to Clevis Pin at mid stroke)	4.955m x 1.25m x 1.35m (length x width x height)	4.955m x 1.25m x 1.35m (length x width x height)
Actuator Dimension (Foot End to Foot End at mid stroke)	5.495m x 1.25m x 1.35m (length x width x height)	5.495m x 1.25m x 1.35m (length x width x height)

Note: The actuators are all double rod actuators (i.e., the left and right chamber effective actuating areas are the same). Hydrostatic bearing at both headers make them frictionless.

Table 1-6 Equipment Drawings

Equipment	Link to Drawing (PDF)
Actuator Assembly (200-9004)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Actuator Assembly 1700kN (200-9004).pdf
Load Cell Assembly (200-9401)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Load Cell Assembly 2000kN (200-9401).pdf
Load Cell Mounting Assembly (200-9412)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Load Cell Mounting Assembly (200-9412).pdf
Pressure Transducer Assembly (000-0388)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Pressure Transducer Assembly (000-0388).pdf
Self Aligning Bearing Assembly (200-9507)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Self Aligning Bearing Assembly (200-9507).pdf
Self Aligning Bearing Assembly (200-9508)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Self Aligning Bearing Assembly (200-9508).pdf

1.3.3 Servo-valves

10 servo valves (labeled as A,B,C,D,E,F,G,H,J,K) are configured to the 5 actuators. The default configuration has Valves A and B assigned to Actuator 1 (±1700KN) (±382 kip), Valves C and D to Actuator 2 (±1700KN) (±382 kip), Valves E and F to Actuator 3 (±1700KN) (±382 kip), Valves G and H to Actuator 4 (±2300KN) (±517 kip), and Valves J and K to Actuator 5 (±2300KN) (±517 kip). If an actuator needs to have three servo-valves mounted, the third valve can be selected from one of these 10 servo-valves. The servo-valve specification is listed below in Table 1-7.

Table 1-7 Servo-valve specification

Servo-Valve Model	SV1200 (Servotest)
Servo-Valve Stages	3
Pilot Valve Model	G772-204(Moog)
Servo-Valve Quantity	10
Flow Rate Capacity (Single Valve)	550gpm @ 20.7MPa (3000psi)
Dynamic Bandwidth	30Hz @ -6db
Working Temperature	< 55C
Servo-Valve Assembly Weight (Single)	Approx 50Kg (including bladder accumulators)
Single Bladder Accumulator Volume and Initial Gas Pressure	10 liter capacity, supply port pressure = 170bar, return port pressure = 10bar
Supply Pressure Ports	38.1mm-6000SAE x 2
Return Ports	50mm-3000SAE x 2

Note: The servo-valve is a 4th order system with certain nonlinear properties. A 30 Hz bandwidth is measured when the spool opening amplitude is equal to 100%. For small opening sinusoid tracking, the bandwidth may go higher to 140 Hz.

Table 1-8 Equipment Drawings

Equipment	Link to Drawing (PDF)
3 Stage Servovalve Assembly (000-1693)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/3 Stage Servovalve Assembly (000-1693).pdf
Servovalve Assembly (000-1396)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Servovalve Assembly (000-1396).pdf

1.3.4 Hydraulic Service Manifold (HSM)

There are 10 HSMs, each connecting one of the 10 servo-valves with the pump-accumulator hydraulic supply system. Each HSM is configured for one servo-valve, providing high pressure, low pressure, and shutoff operations.

The high pressure state is the normal operation state which passes through a maximum flow rate of 2082 liters/min (550 gpm) and a normal supply pressure of 20.7 Mpa - 24.1 Mpa. If the supply pressure is lower than 15 MPa (2176 psi), this state will be disabled.

The low pressure state provides a low pressure of 7 MPa (1015 psi) with an adjustable flow rate of 0~70 liters/min (which is adjusted by a throttle valve). The low pressure state is often used for configuration of the actuators for test preparation.

The shutoff state is used to disconnect the hydraulic supply from the servo-valves or actuators. It is often used after the test is done or when an emergency stop (E-Stop) needs to be activated.

Each of the HSMs have the dimensions of 465 mm x 420 mm x 451 mm (1.5 ft x 1.4 ft x 1.5 ft) (length x width x height). Each HSM connects to a servo-valve using two 38.1 mm (1.5 in) diameter hydraulic hoses for the hydraulic supply pressure line and two 50 mm (2.0 in) diameter hydraulic hoses for the hydraulic return line. The hydraulic pump-accumulator supply system connects to each HSM using two 50 mm (2.0 in) diameter hydraulic hoses for the hydraulic supply pressure line and two 50 mm (2.0 in) diameter hydraulic hoses for the return line. The HSM specification is given below in Table 1-9.

Table 1-9 Hydraulic Service Manifold specifications

Model	B550-3412
Serial No.	6162~6171
Quantity	10
Low Pressure Output	0~7MPa
Low Pressure Flow Rate	0~70liters/min
High Pressure Pass Through	16~28MPa
High Pressure Flow Rate Capacity	2082 liters/min
Low/High Switching Pressure	15MPa
Inlet Pressure Ports	50 mm-6000SAE x 2
Inlet Return Ports	50 mm-3000SAE x 2
Outlet Pressure Ports	38.1 mm-6000SAE x 2
Outlet Return Ports	50 mm-3000SAE x 2

Table 1-10 Equipment Drawings

Equipment	Link to Drawing (PDF)
Solenoid Control Manifold (550-9104)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Solenoid Control Manifold (550-9104).pdf
Hydraulic Control Box 2 (6463)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Hydraulic Control Box 1 (6463).pdf

Hydraulic Control Box 2 (6464)	http://www.rtmd.lehigh.edu/wordpress/uploads/usermanual/drawings/Hydraulic Control Box 2 (6464).pdf

1.3.5 Control Systems

1.3.5.1 Servotest Servo-Controller

The servo-controller (DCS 2000, and referred to herein as Controller), communicates with all of the servo-valves, actuators, transducers, HSM control box and simulation computer (RTMDsim) as part of the servo-control system. The Controller consists of the following components:

The Host Computer (referred to in this Guide as RTMDctrl), is a Windows based PC. The software for system control is called Pulsar which consists of a series of modules such as: Control, Monitor, Limits, Database, Oscilloscope, Data Logger, Reply, Filter and Wavegen. A PID control module is built in. For developing a user's control law, implementation is achieved through Socket building.

The Controller consist of a Digital Signal Processor (DSP) Real-time Control Card (Module 2201), which is plugged into the RTMDctrl. The card contains a TMS320C30 DSP to deliver sustained (33MFLOP) performance in real-time. Sampling rate is set at 1024Hz.

Two External Conditioning 'XBus' Subsystems enclosures are connected to the DSP Controller at RTMDctrl via shielded high speed bus cables. The XBus systems each contain individual power supplies and a backplane bus into which are plugged various input/output cards. All analogue channels have individual 16 bit resolution ADC or DAC systems which convert simultaneously to improve throughput and eliminate signal skew. The cards installed for the five actuators are:

- Five 2202-0 conditioner cards, which process transducer signals, converting them into digital form for the DSP and performs the carrier signal generation for the transducer. Each card serves the load cell conditioning and displacement transducer conditioning for one actuator.
- Ten 2203-0 3-stage servo-valve system drive cards, which take digital data from the XBus and converts to analogue valve drive current. Each card serves one servo-valve such that there are 10 cards configured for these 10 servo-valves.
- One 2206-0 Digital I/O card, which provides a group of digital channels, writable and readable from the XBus.

Two 2207-2 Hydraulic Control Boxes, which operate the Hydraulic Service Manifold (HSM) via solenoid valves switch on/off hydraulic supply to/from servo-valves (one HSM for one servo valve). Each Box can hub 5 HSM control units. Two boxes exist for the 10 HSMs. These boxes are connected to two External Conditioning 'XBus' Subsystems. An emergency stop (E-stop) is configured within.

One SCRAMNet card is hosted in the Controller and connected to the RTMD infrastructure via fiber optical network running a developed Platinum protocol. The SCRAMNet card communicates with the RTMDsim through 64 input and 64 output values, memory assignable, and is intended for controllers up to 8 actuator channels.

The design of the servo-controller system enables control of up to 8 actuators. Currently, the system is configured for 5 actuators. Detailed information of the servo-controller system is given Table 1-11 (some of modules in the Table 1-11 are currently not available at the RTMD facility).

Table 1-11 DCS2000 specification

Control	
Channel x Frequency Product	800Hz (200Hz for up to 4 ch from Q4 1997)
Maximum Channels	32 (to approximately 25Hz)
Maximum Frequency	500Hz (1 channel)
Maximum Control Iteration Rate	4.096 KHz, typically 1.024 KHz or 2.048 KHz
Control Iteration Rate Range	100Hz to 5KHz (102.4 Hz to 4.096 KHz)
Servo Control Resolution	16 bits
Available Control Types	PID, Vibration, Adaptive. Further Types can be added any time. Different control methods can be applied simultaneously to different channels. Load (Force), Displacement, Velocity, Acceleration or any other external input signals. 64, 32 Strain Gauge or LVDT type inputs, plus 32 Current (Charge) or Voltage inputs.
Internally Generated Signals	
Number of Simultaneous Generators	0 to 8 (typical), or more if lower iteration rate
Linking Modes Between Multiple Generators	Linked Delay (0 to 800,000 seconds) Linked Cycles (0 to 200,000 Cycles) Linked Simultaneous Start and Stop
Common Properties	
Frequency Range	30Hz to 400Hz
Instantaneous Frequency Resolution	Better than 1 part in 10^5N
User Frequency Adjustment	To 0.0001Hz
Frequency Accuracy	10ppm/Hz
Frequency Drift	15ppm/C
Individually Adjustable Properties	
Wave Shapes	Sine, Square, and Triangular
Number of Cycles	0.25 to 200,000 cycles in 0.25 cycle steps
Modes	Continuous, Continuous with Soft Start and Soft Stop (soft period adjustable between 0.02 and 800,000 seconds)
Initial Phase Angle	1 degree to 30,000 degrees in 1 degree steps
Sweep Modes	Bi-directional, unidirectional, Number of Sweeps, Sweeping duration, Linear and Logarithmic

Sweep Rates(can be increased on request)	Linear: 0.0001 Hz/s to 10,000 Hz/s Logarithmic: 0.0001 Oct/min to 100 Oct/min
Signal Inputs and Outputs	
2202 2-channel Conditioner Card (2x16bit, 20KHz acquisition, opto-isolated ADC channels on each card. Channels convert simultaneously) (max 32 cards)	1 off 10KHz carrier channel for strain gauge or LVDT type transducers, plus 1 DC channel for current (charge) transducer (i.e. accelerometer) or voltage transducer (i.e. velocity)
2203 1-channel Servo Drive Card (max 32 cards)	1 servo drive amplifier. Can drive multiple two stage of 1 off three stage servo-valves. Has third stage spool control on card and 16 bit self-calibrating opto isolated ADC for monitoring spool position.
2204 4-channel Analog Input Card (max 8 cards)	16bit auto re-calibrating, opto-isolated ADC inputs. Max. input scale ± 10 Volts. Apparent scale software changeable. 4th order (24 dB/oct) 500 Hz low pass anti-aliasing filter on each input.
2205 6-channel Analog Output Card (max 4 cards)	16bit opto-isolated DAAC voltage outputs. Max. output scale ± 10 Volts. Apparent scale can be changed in software.
2206 16-channel Digital I/O Card (max 8 cards)	All channels fully bi-directional, opto-isolated open collector, active high or low in software.
Signal Handling and Monitoring	
Real Time Polynomial Linearization	Individual 5th order (6 terms) equation applied to carrier based transducer inputs.
Scale and Offset Error Reduction	Determination can be carried out at any time, in real-time.
Real Time Valve Linearization	Individual 3rd order (4 terms) equation may be applied to any servo valve output.
Real Time Multiple Version Generation	RMS, Peak, Instantaneous and Mean versions of any signal can be generated.
On Screen Monitors (Number of available monitors limited by Windows resources only)	Any version of an external or internal signal can be displayed in engineering units. Visual update rates: Instantaneous - 1 sec. RMS, Peak and Mean adjustable between 0.5 and 800,000sec.
Trip Settings (trips 'pop-up' on screen)	Can be applied to any conditioned signal. Individually adjustable Max. and Min. levels and Trip actions. Maintains Trip Log.
On Screen Oscilloscopes (max 2 off) Adjustable Time base, Sweep positions and scales.	4 channel, 4K (Max) samples per channel display. Inputs can be any version of any external, internal, or conditioned signal.
Data Logging (adjustable acquisition rate)	Max. 16 channels at 1KHz continuous sampling, saved to Hard Disk Storage in Real Time. Inputs can be any version of external, internal or conditioned signal.
Signal Overload	All inputs and outputs accurate to full scale deflection ± 9% and saturate safely to known values.
Hardware Configuration	All input and output cards have corresponding individual Configuration 'Templates' Windows.
Calibration	
Calibration	Transducers carry calibration, which can be entered into "Templates" at any time. Servotest or User transducers can be

	re-characterized using the optional software Calibration Module.
Real Time Data Analysis and Display	Dynamic Data Exchange (DDE) links with other applications, to update graphs and statistics in Real time. Optional Network DDE support can be provided.
Post Testing Analysis and Display	A wide range of file formats can be produces to support many Data Analysis systems.
Compressor Module	
Number of simultaneous Compressors	0 to 8 (typically), or more if lower iteration rate
Compression Range	± 700dB (internal Floating Point representation)
External Dynamic Range	70dB min.
Rate	Adjustable, 0 to 6dB per cycle.
Counter Timer Module	
Number of simultaneous Modules	0 to 8 (typically), or more if lower iteration rate
Modes of Operation: **Time Duration** **Event/Cycles Count**	 0 to 9 Years, resolution of one control iteration 0 to 4000 million (approx.) resolution of 1 cycle.
Actions on Completion	Indicate, Trip or Shut down.
Sweep Test Control Module	
Adjustable Parameters	Signal Amplitude Profile, Control Breakpoints
Breakpoints	1 to 32
Control Modes	Any signal can be selected as the control parameter between any two breakpoints
Resonance Dwell Module	
Modes of Operation	Phase or Peak Amplitude
Accuracy: **Phase** **Peak Amplitude**	 1 degree of Phase Lock 1dB of Maximum Peak Amplitude
Seek Rate	Adjustable. Same range as frequency sweep rate.
Tracking Filter(s)	Optional Extra: 2nd order (12dB/Oct) or 4th order (24dB/Oct) Low pass or Band pass
Cross Coupling Module	
Number of Simultaneous Modules	0 to 8 (typical), or more if lower iteration rate
Real Time Polynomial Coupling	Individual 5th order (6 terms) equation applied to a selected signal and coupled to another selected signal.
Patching Module	
Number of Simultaneous Modules	0 to 8 (typical), or more if lower iteration rate
Real Time Signal Patching	Up to 3 signals can be individually proportioned and summed to provide a further signal
Pump and Solenoid Control	
Number of Simultaneous Modules	0 to 8 (typical), or more if lower iteration rate
Modes of Operation	Individual or linked
Configuration	Can be connected to any available channel on the Digital I/O cards (type 2206)

Emergency Stop	Hard-wired mushroom head button placed adjacent to keyboard. More buttons can be provided on request
Functionality	Start, Stop, No, Low (if specified) and High Pressure, Pump and Solenoid signals monitored by Trips Module(s)
Operator Panels	
Operator Panels	Optional Panels can be configured and interfaced to the I/O cards on request
Safety Monitoring	
Transducers	Wrong or damaged Transducers, Broken Connections.
Control	Loss of control and/or unexpected actuator behavior
User Inputs	Stop and/or Shut testing on screen. Emergency Stop Button. Multiple User Limits and Limit Actions
Physical	
Host Computer	800MHz, 128MB ram, 13.2GB hard disk, 24" LCD Monitor, 3.5" fdd, 102 key Keyboard, mouse, Servotest DSP card.
Xbus Enclosure (Max 4 off) (can be 19" rack mounted on request)	Max. 16 I/O cards. Fan cooled. Max. Dimensions 480 x 440 x 150mm.
Uninterruptable Power Supply (can be 19" rack mounted on request)	Rated to system requirements, 8 mins full backup (10 more mins on request). Data link to test systems. On screen and audible warnings: Power Fail, Batteries low, Shut down imminent

1.3.5.2 Wineman INERTIA Servo-Controller

The INERTIA control system, developed by Wineman Technology Inc., is a fully customizable real-time servo-hydraulic control and data acquisition system. The system was implemented to supplement the Servotest Controller described in Section 1.3.5.1.

All Servotest actuators, feedback sensors and hydraulics have been upgraded to be compatible with both systems allowing all external components to be interchanged between systems. The system communicates with the existing RTMD IT architecture via SCRAMNet.

The INERTIA software is a LabVIEW based real-time control program that allows the user to fully customize system I/O and hardware layout, system configuration, screen layout and user interface. It also has built in calibration, test profile control, data acquisition and PID tuning utilities.

The INERTIA system is also compatible with ATLSS's existing inventory of hydraulic actuators and both system can be operational the same and time expanding NHERI testing capabilities.

<u>The main features of this software include (See Table 1-12 below for full system details):</u>

- Hardware setup utility for system I/O, conditioning, and control procedures.
- Unlimited control groups with multiple closed loop PIDs for each group (actuator).
- Multiple simultaneous control methods with support for bump-less mode switching.

- Integrated utilities for PID control loop tuning, calibrations, system alarms and profile control.
- Multiple screen capability with customizable graphical displays and layout.
- Independent control and data acquisition rates.
- Integrated test profile editor with control procedure commands and model execution.
- Scalable output for traceable calibration
- Standalone operation for remote test setup without real-time system.

<u>The complete system includes the following components:</u>

- Full size Chassis with distributed power for hydraulics and conditioning, latching relay safety circuit. and built in work station
- Host computer running Windows XP and INERTIA, connected to the real-time PXI controller via Ethernet connection.
- NI PXI-144 14 Slot PXI chassis for PXI hardware
- NI PXI-6251 16 Channel Analog Input – SCXI Interface
- NI PXI-8106 Core 2 Duo 2.16 GHz Embedded Real-Time Controller
- Two NI PXI-6733 High-Speed 16-Bit, 8 channel Analog Output
- Two NI PXI-6514 Industrial Digital I/O with ~~32~~ 64 channels of programmable DIO.
- NI SCXI-1001 12 Slot SCXI chassis for SCXI hardware
- Two SCXI-1102 32-channel Voltage/Thermocouple Input
- Two SCXI-1520 8-channel Universal Strain Gage Input
- Two SCXI-1540 8-Channel LVDT Input
- Five VC2124 Voltage to Current Converters, 2 channels per converter
- SCRAMNet+ SC150 Fiber Optic Shared Memory
- Wineman production rack mount terminal blocks

Table 1-12 INERTIA specification

PID Control	
Control/Output Channels	10 Configured; 16 Available
Loop Rates	1kHz, Variable up to 10kHz
Output Drive	±10 V, ±100 mA
Gain Parameters	Proportional, Integral, Derivative, Feedforward and Model Based Control
Compensation	Amplitude Control, Phase Compensation

Data Acquisition	
Resolution	16-bit
Sample Rates	1kHz, Variable up to 10kHz
Range	Voltage, current, strain gauge, AC LVDT, IEPE, Frequency, digital, thermocouple
Number of Channels	144, Scalable through additional hardware up to 8,000
Calculated Channels	Unlimited custom variables for up to 500 user defined numeric functions
Operator PC Interface	
Host-Target Connection	Ethernet RJ45
Operating System	Windows XP Professional
Drivers	National Instruments LabVIEW Run Time, NI DAQ MX
Utilities	PID Tuning, Data Reporting, Test Editor, User Administration, Screen Editor, Error Monitor, Alarm Monitor
Operator Screens	Unlimited customizable screens
System Configuration	System configuration utility for defining input channels, output channels, shutdown procedures, PID control loops, and alarms
Alarms	Unlimited on any variable
Calibration	
Types	3rd order polynomial curve fit, lookup tables, thermocouple linearization
History	Unlimited calibration history per channel with roll back capability
Coefficients	Automatic calculation or manual entry
Units	Complete customization of engineering units with conversion capability
Test Generation	
Waveform	Sine wave, Triangle, Square, Haversine, Ramps, Holds, Point Playback, Dwell
Number of Channels	Unlimited
Frequency Range	0.0001Hz to 200Hz
Custom Steps	Conditional profile branching, Discrete parameter adjustment
Data Logging	
Number of Log Files	8 independently rate controlled
File Formats	ASCII, TDMS, ATF
Data Rates	Up to Maximum Acquisition Rate
Triggering Modes	Periodic Time, Periodic Cycles, Crash, In-Limit, Out-of-Limit
Trigger Channels	Any System Variable

1.3.6 Data Acquisition

The DAQ Mainframe (also referred to as the Model 6000) is a high-speed data acquisition and conditioning system that acquires data from strain gauges, accelerometers, LVDTs, and thermocouples. The DAQ Mainframe consists of three enclosures housing three different types of I/O modules: (1) Model 6013 for LVDTs and thermocouples; (2) Model 6014 for accelerometers; and (3) and Model 6033 for strain gages. There are a total of 9 modules of Model 6013, 3 modules of Model 6014, and 21 modules of Model 6033. Each module conditions 8 channels. The DAQ Mainframe hosts a SCRAMNet card that broadcasts real time data over a fiber optical network to the RTMDsim and/or RTMDxPC for integrated simulation and control and to the RTMDtele for telepresence. Below is a summary of the description, features, and configuration for the Model 6000 and specifications for the modules for Model 6013, 6014, and 6033.

Model 6000 description:

The 6000 Mainframe has an IEEE-488 interface for control and data output with mounting for 16 input and output modules. It supports up to 31 additional slave enclosures or up to 32,000 channels. A rear mounted fan circulates air to the power supplies and input/output modules. An integral cable tray routes the input and output cables to exit from the rear. All access for channel module installation and service is from the front. The 6000 and 6001 slave have removable doors to facilitate installation and wiring.

Mainframe and slave enclosures that are cabinet mounted should be supported on sturdy mounting rails. A rail set, RAL2, is available from Pacific in sizes that fit most cabinets.

Model 6000 features:

- Up to 1 million samples per second
- 304 channel total expandable to 384
- 24 accelerometers channels (model 6014)
- 72 thermocouple / double ended voltage transducers (model 6013)
- 208 strain gage and single-ended voltage sources (model 6033) 16-bit resolution
- SCRAMNet+ SC150 interfaced equipment
- 2000Hz recording rate over SCRAMNet with all 304 channels
- Selectable channel recording rates for other configurations

Model 6000 configuration:

- Model 6000 Mainframe (128 Channels) expandable up to 15 slaves
- Two Model 6001 Slaves (128 channels capability each)
- Data Storage on computer and/or dump to SCRAMNet (no on-board storage)
- Nine 6013 8-channel voltage boards (Capable of 10kHz/channel)
- Three 6014 8-channel voltage boards (Capable of 10kHz/channel)
- Twenty 6033 8-channel strain gage boards (Capable of 10kHz/channel)
- PI660 Windows based software (Compatible with MTS, MATLAB, Excel, and LabVIEW)

I/O Module 6013 description:

Each channel on the 6013 has a programmable gain, differential input instrumentation amplifier, low-pass filter and sample and hold. Sample and hold outputs are multiplexed to a 16-bit analog-to-digital converter. A regulated, bipolar 12 or 15 Volt supply provides power for transducers like DC LVDTs. Each channel's power is fused by a resettable polyswitch. The companion 6084 thermocouple junction box has a precision temperature sensor that when used together with the 6013 performs cold junction referencing.

I/O Module 6013 features:

- Thermocouple, DC LVDT or voltage
- ±12 or ±15 VDC for transducers
- Voltage substitution calibration
- Gains from 1 to 5,000
- Four-pole, low-pass filter

I/O Module 6014 description:

The 6014 has eight channels of AC or DC coupled programmable gain instrumentation amplifier, filter and sample and hold. A high-level multiplexer selects each channel for digitizing and output to the 6000 data bus. It includes constant current excitation for use with current driven transducers. The 6014 is primarily for use with transducers that have a built-in, low-impedance output amplifier or charge to voltage converter. It may also be used with voltage inputs where AC coupling is desired. AC or DC coupling and current excitation are selected by jumpers for each channel. A continuous analog output is available for monitoring and output to tape recorder or display.

I/O Module 6014 features:

- Excitation for current driven transducers
- Gains 1 to 5,000 with 0.05% accuracy
- AC or DC input coupling
- Automatic zero

I/O Module 6033 description:

Each channel is a complete transducer signal conditioning amplifier with excitation voltage regulator, automatic bridge balancing, differential instrumentation amplifier and sample and hold. The sample and hold outputs are multiplexed to a 16-bit analog-to-digital converter. The 6033 features four levels of programmable output alarms and excitation short and open alarms.

I/O Module 6033 features:

- ¼, ½ and full bridge transducers
- Programmable excitation, 0 to 12 Volts
- Automatic balance and zero
- Shunt and voltage substitution calibration
- Four-pole, low-pass filter

1.3.7 Instrumentation

1.3.7.1 Advanced Instrumentation

3D Digital Image Correlation:

- Trilion Aramis 3D Image Correlation System. Specifications are given in Section 1.8.1 of this guide.

1.3.7.2 Conventional Instrumentation

Displacement Sensors:

- Six (6) Temposonic position sensors with a ±30 in stroke, input range +9 to +28.8 VDC, and output range -10 to -10 VDC.
- Six (6) Temposonic position sensors with a ±44 in stroke, input range +9 to +28.8 VDC, and output range -10 to -10 VDC.

Figure 1-7 Temposonics

Accelerometers:

- Triaxial capacitive accelerometers with ±10 g range, 180 Hz frequency bandwidth, and 200 mV/g sensitivity.

Figure 1-8 Triaxial Accelerometer

- Five (5) monoaxial accelerometers with ±10 g range and 300 Hz frequency bandwidth.

Inclinometers:

- Bi-axis dynamic inclinometers with a 150 Hz sampling rate, 360-degree inclination angle range, and a resolution to within 0.1 degrees.

Figure 1-9 Inclinometer

LVDTs:

- Macro Sensors' DC 750 Series of 3/4 inch (19 mm) DC-operated LVDTs sensors are designed for a wide range of position measurement applications. They use built-in electronics to provide the desirable features of an AC-LVDT, such as frictionless operation and dynamic response, with the added convenience and simplicity of DC input and pre-calibrated DC output.

Figure 1-10 LVDTs

Differential Pressure Transducers:

- Five (5) 210-65-010 Differential Series pressure transducers especially designed to make differential measurements at full system pressure in Skydrol® fire resistant aviation hydraulic fluid applications. With two separate sensing elements to measure the pressure at the input ports, the 210-60-090 Differential Series provides an output directly proportional to the pressure difference at the two ports. It is temperature compensated, and is recommended for applications which require highly accurate measurement.

Figure 1-11 Differential Pressure Transducer

1.4 RTMD IT Systems

The RTMD IT Infrastructure systems are comprised of seven major systems and a shared memory protocol:

- **RTMDctrl:** This represents both the Servotest Pulsar DCS controller and the Wineman INERTIA controller. These systems are PID controllers for operating the NHERI and ATLSS actuators. Both systems are connected to the RTMD IT infrastructure via SCRAMNet and operate at 1024Hz.
- **RTMDdaq:** This is a computer that interfaces directly with the Pacific Instruments PI6000 data acquisition system through PI660 Windows software for the purposes of configuration and monitoring data acquisition. This system has an active role in configuration and a passive role in monitoring data acquisition, since data acquisition data is shared with other RTMD systems by means of the SCRAMNet interface.

- **RTMDxPC:** This is a computer that runs Mathworks Simulink Real-Time software package, formerly xPC Target. This dedicated kernel guarantees reliability and timing for compiled models. This system is compiled with Simulink models, provides commands to and receives feedback from RTMDctrl over SCRAMNet and synchronizes data from RTMDdaq and RTMDctrl over SCRAMNet. It provides the ability to integrate data acquisition signals or controller feedback signals for various testing methods. It also provides an external timing signal to the data acquisition to ensure time synchronization. The testing methods are discussed in Section 2.
- **RTMDsim:** This is a Windows based PC which configures and coordinates various testing methods and communicates with the RTMDxPC. This host system provides a configuration interface to the RTMDxPC through MATLAB and Simulink. It also provides a platform for running non real-time and distributed-based testing methods.
- **RTMDtele:** This is a server that interfaces with the SCRAMNet shared memory bus, and provides a synchronized source of data from the PI6000 mainframe, the controller, RTMDsim and RTMDxPC for telepresence using Data Turbine.
- **SCRAMNet:** The underlying communications mechanism between the DAQ mainframe, RTMDsim, RTMDxPC, RTMDtele, and controller based on a proprietary shared memory bus and fiber optic network technology. A LinkXchange switch provides a configurable mechanism for mapping each of the systems attached to the network.
- **RTMDws:** This is the web camera server for video telepresence and a public and local cloud data server.
- **RTMDrepos:** This is the local data repository server for the RTMD facility. This system is a 32TB DroboPro FS dual-redundancy RAID. This is used as the local backup library for experiment data and metadata and system backups along with a document library.

The above systems enable integrated control, where the user has the ability to configure the systems for an experiment. The procedure for configuring the systems is discussed in Section 1.6, Configuring an Experiment.

In the following section, a description of how the systems are integrated together during an experiment is laid out in order for users to gain an understanding of the system functionality.

1.5 Integration of RTMD IT Systems

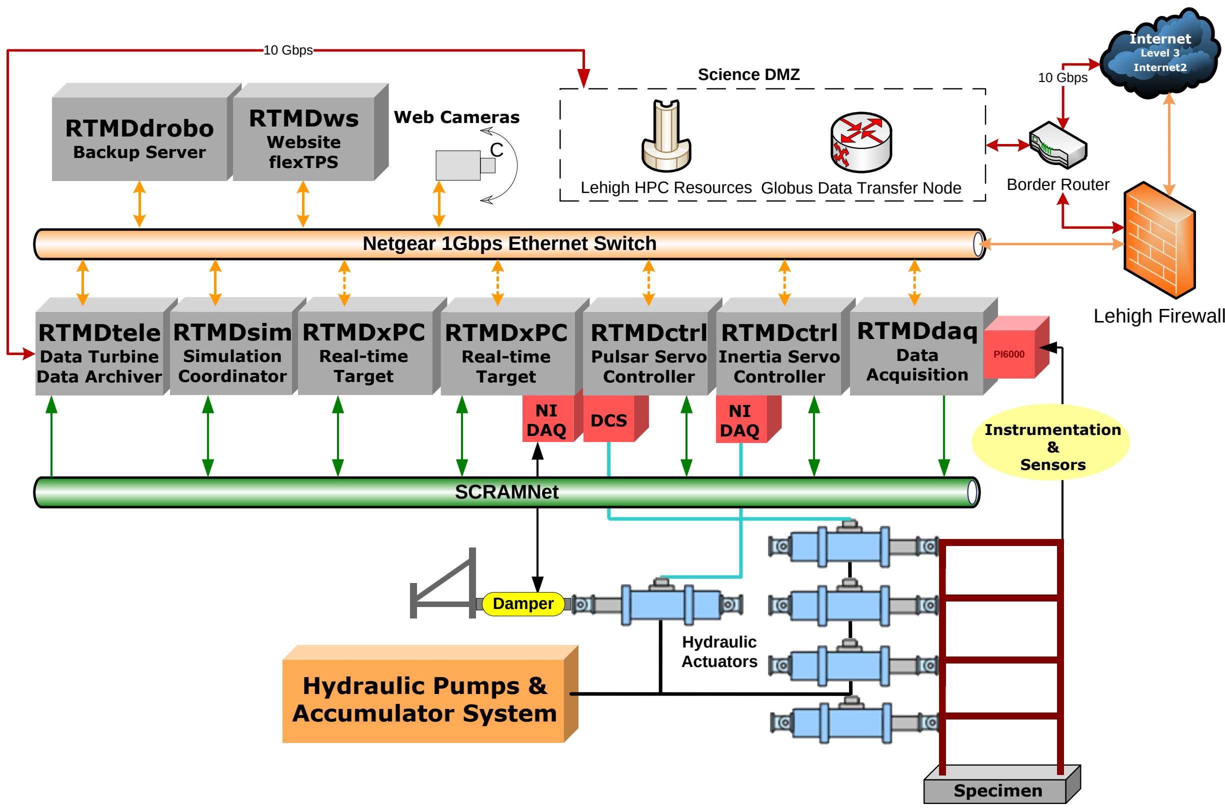

Figure 1-12 RTMD servo-hydraulic control and IT Infrastructure

The NHERI Lehigh RTMD EF IT infrastructure, shown above in Figure 1-12, provides the framework for data and metadata to be transferred among systems. The systems include the RTMDtele (real-time telepresence server), RTMDsim (simulation coordinator), RTMDxPC (real-time simulation target), Controller (real-time controller), RTMDctrl (real-time control workstation), DAQ Mainframe (real-time data acquisition system), RTMDdaq (real-time data acquisition workstation), and RTMDrepos (RTMD local data repository). The RTMDctrl, RTMDsim and RTMDdaq are user interfaces with the Controller, RTMDxPC and the DAQ Mainframe, respectively. RTMDsim and RTMDxPC have a host-target relationship via Ethernet cable which enables the user to develop models on the host and download to the target. RTMDdaq, RTMDctrl along with RTMDsim, RTMDxPC and RTMDtele are all connected via SCRAMNet enabling real-time, synchronized data transfers. The data exchange for one data block (4 bytes) across SCRAMNet shared memory bus occurs within 200 nanoseconds, facilitating synchronized real-time testing capabilities at the 1024Hz control rate. A data structure for SCRAMNet is defined that includes multiple states for commands and feedback signals, enabling advance servo-hydraulic control laws to be implemented and sophisticated testing methods to be performed along with creating streams of data for telepresence.

While an experiment is being conducted, RTMDtele provides a single point of access for streaming data to local and remote participants. RTMDws provides an interface to the live cameras in the RTMD lab along with a cloud data server to share files. As gateways, these systems provide a layer of functional protection for controlling an experiment, while also providing access to experimental data and offsite control in a moderated manner. The RTMDrepos functions as the repository for data after an experiment. After the experiment, all data and configuration information is archived to this location and curated at designsafe-ci.org.

1.6 Configuring an Experiment

Experimental researchers planning on conducting an experiment must first provide the details for performing the experiment. A researcher will then need to access configuration programs to configure the RTMDdaq, RTMDsim, RTMDxPC, RTMDctrl, RTMDtele along with setting up a project at DesignSafe-ci.org. These configuration programs generate configuration information for data acquisition, simulation, control and telepresence applications as part of integrated simulation control that are specific to the experiment to be performed. Each of these required steps is briefly described below.

DesignSafe-CI: The Project PI must register the project and create a workspace. All data, metadata, sensor plans, specimen details and configuration files will be curated through this environment.

RTMDdaq: A sensor list is defined for data acquisition of sensors. This includes choosing the channel types, entering descriptive information, location information, calibration factors and activating the channel for inclusion in the experiment. Screens for shows real-time acquired data are also configured here.

RTMDsim/RTMDxPC: User will configure his/her simulation or experiment through the RTMDsim using Matlab. If performing a real-time experiment, the Simulink model is downloaded to the RTMDxPC. Users are referred to Section 2 for more information on types of test methods available.

RTMDctrl: The user will configure the hydraulic control software to enable servo-valves, actuators and set PID parameters and actuator limits along with configuring the channel mapping for the SCRAMNet and integrated control.

RTMDtele: The user will configure the telepresence streaming and data archiving on the RTMDtele system. This application provides an interface for the user to define which channels from the RTMDdaq, RTMDsim/RTMDxPC and RTMDctrl are streamed.

RTMDws: The user will configure video streams from available network enabled cameras.

The servo-hydraulic equipment that is maintained and operated at the RTMD is of dynamic nature. It is the responsibility of the RTMD equipment site to ensure that the equipment is operated in a safe manner that does not present a risk to the safety of laboratory staff and researchers present in the lab as well as any potential of damaging the equipment. All testing proposed by the researchers will need to be reviewed by the RTMD staff prior to testing to ensure the testing protocol does not present a risk to the safety of laboratory staff and researchers of any potential for damaging the equipment. The review process will involve providing a test matrix to the RTMD Research Engineer or RTMD IT Manager with all of the details associated with the testing protocol, including the demand to be imposed on the equipment such as maximum actuator stroke, velocity, force, frequency of loading (when repetitive loading histories such as sinusoidal loading as well as band limited white noise tests are involved). It is expected that state-of-the-art procedures be used to develop the prediction for the demand on the equipment. The method and procedure used to arrive at the prediction of the test specimen response that imposes the demand on the equipment must be provided. The researchers must also include a statement as to what is the expected damage that will occur to the test specimen during each test. No testing will commence until either the Lehigh Equipment Site PI, Co-PI, or Research Scientist of the RTMD has approved in writing the test matrix. No deviation from the test matrix is permitted without the approval of either the NHERI Lehigh EF PI, Co-PI, or RTMD Research Scientist/Engineer.

Once the above steps are completed, it is necessary for all the systems to be validated. Balancing and calibrating sensors requires RTMD technical support. Control programs are developed and validated through hydraulics off simulations with the RTMD IT Manager. Limits and hydraulic control parameters are defined with assistance from the RTMD Research Engineer. Telepresence applications are also developed with assistance from the RTMD IT Manager. All aspects are tested in a safe manner before any experiment is conducted.

1.7 Conducting an Experiment

When all steps in Section 1.6 are completed, the experiment is ready to be performed. Listed below are the typical steps a user will take to perform an experiment from start to finish.

- User will verify with the RTMD IT Manager that data acquisition system is valid and operational on RTMDdaq.
- User will verify with the RTMD IT Manager that hydraulic control is stable using RTMDctrl.
- User will verify with the RTMD IT Manager that RTMDtele is streaming configured data streams.
- User will verify with the RTMD IT Manager that RTMDws is streaming required web cameras.
- User will verify with the RTMD IT Manager that a previously approved[2] simulation model is loaded on the RTMDsim/RTMDxPC.

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[2] The Equipment Site Director, NHERI Research Engineer, or Equipment Site Director must approve all simulation models before a specimen is tested.

- User will verify with ATLSS Laboratory Operations Manager and RTMD Operations Manager that all safety limits are in place and operational.
- User will confirm with the ATLSS Laboratory Operations Manager, RTMD IT Manager and RTMD Operations Manager that all steps have been executed and testing is ready to be performed.
- User will run the experiment and collect all data required from the RTMD systems.
- User will confirm with the ATLSS Laboratory Operations Manager and RTMD Operations Manager that all testing is completed and have the hydraulics system shut down.
- User will stop the data acquisition and telepresence streams with help from the RTMD IT Manager.

1.8 Advanced Instrumentation

1.8.1 3D Digital Image Correlation

The ATLSS Engineering Research Center possesses a Trilion ARAMIS 3D Image Correlation System, which provides three-dimensional deformation and strain distributions measurements for objects. The object under load (static or dynamic) is viewed by two CCD cameras. A random or regular marking pattern is applied to the object's surface, and will deform along with the objects. The deformation of the pattern under different loading conditions is recorded by the CCD cameras. Using image correlation and photogrammetric principles, 3D Coordinates of the surface of specimen are tracked at each stage of load, and the resultant deformations at every point on the surface can be calculated precisely.

The ARAMIS system includes:

- ARAMIS 3D High-Resolution System, including two high resolution CCD cameras, 2 mega-pixel each, 12 frame per second (fps) maximum; three pairs of lenses; camera cables; illumination system; support bars and tripods.
- Ultra-High-Speed ARAMIS 3D Imaging System, including two high resolution high speed cameras with 1024×1024 pixels at 3000 fps, 512×512 pixels at 10k fps, or 256×256 pixels at 30k fps; two pairs of lenses; camera cables; illumination system; support bar and tripod.
- Image Processing System and ARAMIS Analysis Software.
- Trigger box and measuring volumes for calibration.

Figure 1-13 A complete Aramis system consists of an image processing computer and a pair of cameras

1.9 Data Management Plan

1.9.1 Data Description

The project will utilize the computational, experimental, and IT network facilities located at Lehigh University. Experimental, computational, and simulation data developed will be archived to enable re-use by researchers. The NHERI Lehigh RTMD EF web site provides a local repository for experimental, computational, and simulation data for the project. Users are able to upload data to the NHERI data repository through the internet connection between the NHERI Lehigh RTMD EF and NHERI.

The data management plan contained here is associated with physical experiments and numerical simulations performed by users of the facility. The researchers will be given training and assistance by the NHERI Lehigh EF IT Systems Manager, but will responsible for uploading all of their data, including: the metadata that describes the experimental setup report; unprocessed experimental data; converted experimental data; metadata that describes the numerical simulation models; numerical simulation model input data; numerical simulation model output data; numerical simulations processed data; pictures and video.

Data to be included under Data Management at the NHERI Lehigh RTMD EF includes the following categories:

- Unprocessed or raw experimental data in ASCII or binary format obtained by data acquisition and control hardware (Pacific Instruments, Servotest, Wineman, Mathworks, National Instruments).
- Converted and derived data sets from unprocessed data obtained through computational software (MATLAB, Microsoft Excel).
- Computational models including analytical data in ASCII format.

- Experimental photos and videos through web cameras, point and shoot cameras and camcorders.
- Software developed which generates NHERI related project data.

All data will be made available raw and uncorrected, as well as in converted forms in engineering units. In addition, pictures and videos will be part of the data collection. Annotations will be used to indicate relevant information describing events during each test, and the data will be documented to enable a qualified researcher to reproduce the simulation or test and generate the derived data throughout the lifetime of data repository.

1.9.2 Data and Metadata Formats

The procedures for data archiving will follow the NHERI data repository standards for metadata. The data hierarchy is defined below.

- *Project*: a Project represents an overall research project, which includes one or more experiments/numerical simulations.
    - *Experiment*: an experiment represents a physical test or a computational simulation.
        - *Trial*: a trial is associated with an experiment or a simulation. Multiple trials may be applied to the same experimental or simulation set up.
            - *Repetition*: a repetition is associated with a trial and represents the application of the same trial without any change to the test set up or trial parameters.

1.9.3 Data Archiving on Local Repository

The NHERI Lehigh RTMD EF maintains a redundant and scalable network attached storage system (RTMDdrobo) which contains all data and documentation related to NHERI. This system is tightly integrated into the RTMD IT architecture and is available as a mapped system to any workstation or server. This system provides dual disk redundancy which ensures that the data remains safe and accessible to users even if as many as 2 drives fail at any given time. This system is protected by the ATLSS firewall and the Lehigh University firewall. Lehigh also utilizes an offsite backup system to guarantee that data is stored safely offsite in case of catastrophic disaster. Data is organized into a file-folder structure that mirrors the NHERI data model format and is uploaded to the NHERI data repository within 24 hours of test completion via a 10Gbps Internet2 connection or up to 10Gbps through the commodity Internet connection. Typically, files are named using a “testname_date.[ext]” format while folders are appropriately named for sets of trial data. Access to the physical RTMDdrobo system is limited to the NHERI Lehigh RTMD IT Manager and is handled with the utmost care and discretion for privacy, security and integrity reasons.

The data acquired and preserved in the context of this proposal will be further governed by Lehigh University's policies on intellectual property, record retention, and data management. The details of this policy can be found at:
https://www.lehigh.edu/~policy/documents/10-05-2011_Combo_Policy_for_Web.pdf

1.10 Cybersecurity Plan

The NHERI Lehigh RTMD Equipment Facility (Lehigh EF) at Lehigh University's ATLSS Engineering Research Center is an awardee of the NSF-funded NHERI program. DesignSafe is the cyber-infrastructure for NHERI and is located at the Texas Advanced Computing Center (TACC). The NHERI Lehigh EF is an integrated member of the DesignSafe team. Cybersecurity protocols are enforced at both the TACC site and the NHERI Lehigh EF to meet NSF requirements. TACC, as the NHERI-CI lead, establishes and implements the NHERI-wide cybersecurity policy and procedure to which the NHERI Lehigh EF adheres.

Roles and Responsibilities

Library and Technology Services (LTS) at Lehigh University is charged with developing and maintaining a secure, fault-tolerant, high-performance campus technology infrastructure to support instruction, research, administrative activities and university communication and outreach. Under this broad mandate, LTS is responsible to develop and promulgate standards which will ensure that the centrally-supported technology infrastructure is secure and operational.

Lehigh University's Information Security Officer is responsible for the enforcement and implementation of the campus-wide cybersecurity policy noted above. The NHERI Lehigh EF falls under the umbrella of the University's cybersecurity plan. The NHERI Lehigh IT Manager is responsible for enforcing the cybersecurity policies and protocols at the NHERI Lehigh EF. The responsibilities include, but are not limited to:

- Operating system integrity
- Malware and virus analysis
- Off-site data backup risk mitigation in case of breach
- Securing physical systems under key lock and ID card access
- Credential administration for facility, staff and students at the Lehigh EF for NHERI related system usage
- Coordinate with LTS for updated University cybersecurity policies
- Coordinate annual security audits with TACC

In the absence of the NHERI Lehigh IT Manager, the ATLSS IT Manager assumes all roles and responsibilities at the NHERI Lehigh EF.

Risk Assessment

LTS reserves the right to scan network-connected hosts to understand what resources are connected to the network and the associated vulnerability of each. LTS will provide advanced notification to the NHERI Lehigh EF prior to initiating such activities. LTS will perform an ongoing assessment of the performance, utilization, and security of the core network and network subnets. Sub-nets or network-attached devices that pose a risk to the broader network community will be considered for removal from the network until the risk is reduced or eliminated. Action taken will depend on the severity of the discrepancies and the associated vulnerability of the network. To that end, LTS will take all reasonable steps, consistent with the risk posed, to help the NHERI Lehigh EF resolve the non-compliance issue.

For all Lehigh EF Linux-based servers, Linux Malware Detect software is run weekly to investigate for any potential intrusions. Windows-based systems utilize Microsoft Security Essentials for potential intrusions or viruses.

Each NHERI awardee will participate in a NHERI security group with appropriate members from each site. This security group will ensure that best practices are flowed on Incident Response (IR), best practices, and security awareness. In addition, a yearly audit of all NHERI resources will take place and a gap analysis will be created. Any findings in the gap analyses will be reviewed by the NHERI CISO and recommendations made for resolution of those gaps.

Technical Safeguards

Lehigh University's network contains multiple levels of firewalls designed to limit the ability of intruders to access the computers beyond those firewalls. Lehigh University has installed a border firewall system between the campus network and the Internet. These firewalls operate in a "default deny" environment wherein all connections from off campus computers are denied unless specifically allowed through the firewall. The border firewalls are stateful firewalls which keep track of the state of any network connections passing through them. In this regard, any network protocol which exits Lehigh University's network utilizing one network port, but replies to Lehigh on another port, will operate without the need of a firewall exception.

Outside users are recommended to utilize VPN to connect a single off-campus computer to the Lehigh University network. Exceptions for inherently insecure protocols such as telnet (port 23) or ftp (port 21) will not be granted. All requests must include the Lehigh University faculty or staff member responsible for maintaining the security of the computer corresponding to the IP address for which the exception is requested.

Local server and workstation firewalls are enabled at the NHERI Lehigh EF to ensure any malicious activity on the Local Area Network does not affect the NHERI-related systems.

Administrative and Physical Safeguards

Usage of any NHERI Lehigh EF system requires a Lehigh University authenticated username and password. Rooms containing NHERI related equipment are restricted by ID card and key access. Lehigh University user account passwords expire every 180 days.

Policy and Procedures

LTS has developed, published and maintains a set of standards which ensures that network segments and connections can interact appropriately with the campus-wide network, that network security is maintained, and that network hardware and software is maintained. Standards include but are not limited to such issues as:

- Electronic interface
- Cable plant used within the subnet
- Internal configuration
- Security practices
- Use of appropriate network monitoring procedures
- Up-to-date network diagrams
- Appropriate server security facilities in place (including anti-virus and software patch levels)
- Currency of operating system release levels
- Backup procedures are in place and adequate
- Hardware maintenance and/or support is in place
- Software maintenance and/or support is in place
- Departmental contact is assigned and available on-call
- Appropriate technical documentation is available
- All applicable software has been appropriately licensed

All devices connecting to the Lehigh University network, including the NHERI Lehigh EF, must be capable of complying with LTS-selected standard network protocols.

Awareness and Training

LTS has the responsibility to disconnect from the network any network subnet, wireless access point, server, computer, or any other network-connected device that has been identified as being the source of any action which:

- Violates applicable "conditions of use" policies
- Violates local, state, federal or international laws
- Is determined to be a nuisance or potential nuisance
- Is determined to be compromised or is likely to be compromised
- Is interfering with the security or performance of the broader infrastructure

LTS will notify the appropriate departmental contact of the nature of the “violation” and assist the departmental contact to cure the violation.

1.11 Payload Project Protocol

1. All ongoing and newly funded projects at the NHERI Lehigh Experimental Facility are posted on the site’s website to enable researchers to identify potential payload project opportunities.

2. Interested payload researchers should review the posted information for the ongoing/new project scope, schedule, and additional relevant data to determine feasibility of proposing a payload project.

3. If additional project detail is required, payload researchers are encouraged to contact project PI directly to foster collaboration towards the project.

4. Payload researcher must gain approval of existing project PI to payload onto the existing project. PI and payload researcher are both required to inform NHERI Lehigh EF Operations Manager of such approval and subsequent scope and available technical details of the proposed payload project to gain NHERI EF approval for reasons of technical feasibility and safety. Technical details should include the following:
    1. Scope of work
    2. Testing plan
    3. Schedule
    4. Required Equipment and Other Resources

5. Instrumentation Plan
6. Data Management Plan
7. Payload demolition and/or removal plan

NHERI Lehigh EF reserves the right to decline the payload project if prior approval is not provided by project PI and communicated to NHERI Lehigh Operations Manager.

5. Funding source for payload project needs to be identified (to determine if funding is NSF or non-NSF funded) and communicated to NHERI Lehigh Operations Manager in order for payload project budget and impact on NHERI Lehigh Operations and Maintenance budget to be identified by NHERI Lehigh EF.
   - For budget planning, payload researcher is referred to the NHERI Lehigh EF website at https://lehigh.designsafe-ci.org under Resources in order to access key budget development information for operational services and equipment provided by NHERI Lehigh EF.
   - Payload researcher needs to also identify additional budget requirements that are necessary to achieve payload project deliverables through communication with project PI.

6. Once a payload project is awarded funding, a Research Participation Agreement, or similar agreement, will need to be developed between all parties involved, including existing project PI, payload project PI, and the NHERI Lehigh EF prior to any effort towards the payload project.

7. The Research Participation Agreement, or similar agreement, will include, but not be limited to:
   1. Identification of parties
   2. Scope of Work and Testing Plan
   3. Schedule with Milestones
   4. Budget
   5. Responsibility of Costs
   6. Intellectual Property Terms and Conditions
   7. Data Management Plan
   8. Risk Management Plan

8. The payload project schedule will be developed by the NHERI Lehigh EF in conjunction with the overall NCO scheduling function and the ongoing project schedule.

2 Test Methods & Data Analysis

This chapter describes the test methods that are available at the NHERI Lehigh RTMD EF. These methods include: (1) quasi-static testing; (2) hybrid simulation (HS) which includes real-time hybrid simulation (RTHS); and (3) distributed hybrid simulation (DHS). The quasi-static method of testing is well understood, and is not discussed in this Manual. Aspects and an overview of the remaining test methods are given.

2.1 Dynamics of a Structure Subjected to Earthquake Motions

Figure 2-1 shows a simple example of a planar four-story shear frame structure subjected to an earthquake. The foundation of the four-story shear frame is subjected to the ground acceleration history $\ddot{x}_g(t)$. The equations of motion (Chopra, 2001) can be shown to be equal to:

$$\mathbf{M}\ddot{\mathbf{X}}^t(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = \mathbf{0} \tag{2.1}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, $\ddot{\mathbf{X}}^t(t)$, $\dot{\mathbf{X}}(t)$, and $\mathbf{X}(t)$ are the mass matrix, viscous damping matrix, stiffness matrix, total acceleration vector, relative velocity (to the foundation) vector, and relative displacement (to the foundation) vector. The total acceleration, $\ddot{\mathbf{X}}^t(t)$, is related to the acceleration relative to the support $\ddot{\mathbf{X}}(t)$, and ground acceleration $\ddot{x}_g(t)$ as follows:

$$\ddot{\mathbf{X}}^t(t) = \ddot{\mathbf{X}}(t) + \mathbf{i}\ddot{x}_g(t) \tag{2.2}$$

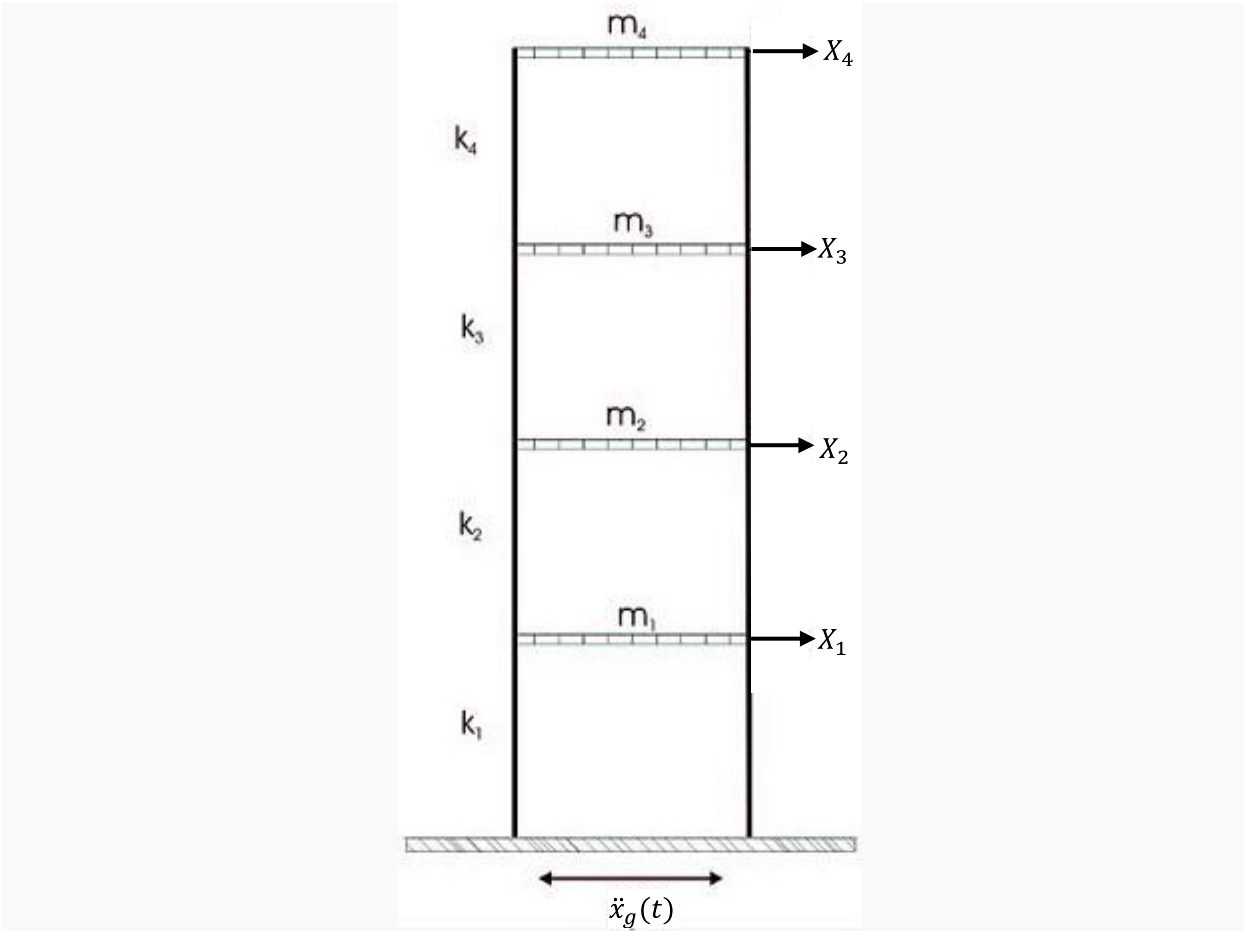

Figure 2-1 Shear building subjected to earthquake ground accelerations

In Equation (2.2), $\mathbf{i}$ is the influence vector representing the displacements of the mass of the structure resulting from the static application of a unit ground displacement. Upon substituting Equation (2.2) into Equation (2.1):

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = -\mathbf{M}\mathbf{i}\ddot{x}_g(t) \tag{2.3}$$

Equation (2.3) implies that the structure can be analyzed as a structure that is supported on a fixed foundation and subjected to an effective force vector $\mathbf{F}(t) = -\mathbf{M}\mathbf{i}\ddot{x}_g(t)$. If the restoring forces, represented by the third term on the right hand side of Equation (2.3), are replaced by a more general restoring force vector $\mathbf{R}(t)$, (which can include non-linearities) the equations of motion become:

$$\mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = \mathbf{F}(t) \tag{2.4}$$

The testing methods (HS, RTHS, and DHS) at the RTMD earthquake simulation facility are based upon the equations of motion in Equation (2.4). More complicated structures can be tested at the RTMD earthquake simulation facility than the one shown in Figure 2-1, including structures with rate-dependent components (e.g., semi-active MR dampers), multi-directional earthquake loading and geometric and material non-linearities.

2.2 Hybrid and Real-Time Hybrid Simulation

The hybrid simulation (HS) method, also known as the pseudo-dynamic test method is an efficient alternative to more expensive shake table test method. The concept of HS was first introduced in the late 1960s by Japanese researchers (Hakuno et al., 1969). The idea of this simulation is to combine both analytical and experimental methods together to form a hybrid simulation method. In this method, the equations of motion (Equation (2.4)) are solved analytically using a step-by-step direct integration algorithm and the computed displacements are imposed on an experimental specimen using either quasi-static jacks or hydraulic actuators based on an extended time scale. The restoring forces from the experimental specimen are measured and used to subsequently integrate the equations of motion for the next time step. The simulation is performed in a quasi-static or pseudo-dynamic manner because the dynamics effects are accounted for analytically through the equations of motion. Since its inception, the HS method has undergone significant development and advancements. A major advancement in HS was the introduction of the concept of substructuring. In the present day HS which is based on substructuring, only the critical parts of a complete system are modeled physically in a laboratory, termed as the experimental substructure, and the rest of the system is modeled analytically, termed as the analytical substructure. This technique eliminated the need for a large laboratory to accommodate a large-scale specimen and enabled researchers to include a larger system in a simulation. Thus, simulation of system and local physical component response was made more economic and efficient.

The time discrete equations of motion for HS based on substructuring can be written as follows:

$$\mathbf{M}\ddot{\mathbf{X}}_{n+1} + \mathbf{C}\dot{\mathbf{X}}_{n+1} + \mathbf{R}^{a}_{n+1} + \mathbf{R}^{e}_{n+1} = \mathbf{F}_{n+1} \tag{2.5}$$

where $\mathbf{M}$ and $\mathbf{C}$ are the analytically modeled mass and damping matrices, respectively; $\mathbf{R}^{a}$ and $\mathbf{R}^{e}$ are the analytically determined and experimentally measured restoring forces, respectively; and n is the integration time step index. Various direct integration algorithms have been developed/used to solve Equation (2.5) or its weighted variants. The implemented HS method in the RTMD earthquake simulation facility provides a user with the option to choose from a wide variety of explicit (e.g., CR algorithm, KR-α method, MKR-α method, and SE-α method) and implicit (e.g., HHT-α method) direct integration algorithms. Interested readers are referred to Kolay (2016) and Mercan (2007) for details on the explicit and implicit direct integration algorithms, respectively, available at the RTMD facility. However, the explicit algorithms that feature unconditional stability and controllable numerical dissipation (e.g., KR-α and MKR-α methods) are preferred in large-scale HS (Kolay, 2016).

Often time, a HS is required to be performed at the true time scale in order to investigate the rate dependent behavior of the experimental substructure. For example, an experimental substructure with rate dependent seismic hazard mitigation devices. This method of testing is referred to as the *real-time hybrid simulation* (RTHS) method. The real-time nature of RTHS introduces many challenges compared with HS including that the computation at each time step needs to be completed in real time within the chosen integration time step size and the servo-hydraulic actuators need to be accurately controlled so as to avoid any amplitude error and time delay in the measured specimen displacement. Because of the real-time nature of the simulation, the measured restoring force vector $\mathbf{R}^e$ (see Equation (2.5)) in an RTHS includes the inertia and damping forces as well. Therefore, the analytically modeled mass matrix $\mathbf{M}$ and the inherent damping matrix $\mathbf{C}$ need to be modeled appropriately so as to exclude the contributions of the experimental substructure which are already accounted for through the physically measured restoring forces. In what follows, a background on RTHS is provided with a brief description of the various components involved.

Consider the structural system shown in Figure 2-2(a) having a linear damper in the first story and a nonlinear damper in the second story that is subjected to seismic ground excitation. Also consider that for the seismic response simulation, the structural system excluding the nonlinear damper in the second story can be modeled accurately. Therefore, an RTHS is considered as a means of simulating the seismic response of the system, where the nonlinear damper is modeled physically in a laboratory (experimental substructure) and the remaining part is modeled numerically using the finite element method (analytical substructure) as shown in Figure 2-2 (b). Now the equations of motion for the complete hybrid system can be described by Equation (2.5). It should be pointed out that the analytically determined restoring forces $\mathbf{R}_{n+1}^a$ may be a function of displacements and velocities, that is, $\mathbf{R}_{n+1}^a = \mathbf{R}^a(\mathbf{X}_{n+1}^a, \dot{\mathbf{X}}_{n+1}^a)$ as in the present case due to the analytical modeling of the linear damper (see Figure 2-2 (b)). Now, for each time step the equations of motion in Equation (2.5) need to be solved for the hybrid system in real time throughout the simulation. As shown in Figure 2-2 (b), the components involved in an RTHS can be divided into three primary modules: (i) simulation coordinator, (ii) analytical substructure, and (iii) servo-hydraulic actuator control and experimental substructure.

2.2.1 Simulation Coordinator

The role of the simulation coordinator is to solve the equations of motion in Equation (2.5) and generate command displacements $\mathbf{X}_{n+1}$ and velocities $\dot{\mathbf{X}}_{n+1}$. These commands are then divided into their analytical $\mathbf{X}_{n+1}^a$, $\dot{\mathbf{X}}_{n+1}^a$, and experimental $\mathbf{X}_{n+1}^e$, $\dot{\mathbf{X}}_{n+1}^e$ parts corresponding to the associated substructures DOFs. The simulation coordinator is also responsible for receiving the restoring forces $\mathbf{R}_{n+1}^a$ and $\mathbf{R}_{n+1}^e$ from the analytical and experimental substructures, respectively. As noted earlier, various direct integration algorithms are available at the RTMD facility. However, it is recommended that either the KR-α or the MKR-α method be used because of their favorable numerical characteristics, namely explicit formulation, unconditional stability, second-order accuracy, and controllable numerical dissipation. Interested readers are referred to Kolay et al. (2015) and Kolay (2016) for the detailed implementation procedure of the KR-α and MKR-α methods.

2.2.2 Analytical Substructure

The analytical substructure, shown in Figure 2-2 (b), is responsible for determining the restoring forces $\mathbf{R}_{n+1}^{a}$ based on the command displacements $\mathbf{X}_{n+1}^{a}$ and velocities $\dot{\mathbf{X}}_{n+1}^{a}$ using a state determination procedure. The analytical substructure can be modeled using either OpenSees (OpenSees 2016) or HbridFEM (Karavasilis et al. 2012), where the latter is a finite element (FE) program developed at the facility using the MATLAB and Simulink software platform (MATLAB, 2015) for conducting nonlinear time history analysis and RTHS. In the HybridFEM, various material and element modeling options are available for creating FE models of complex analytical substructures. The material library of the HybridFEM currently includes elastic, bilinear elasto-plastic, hysteretic, Bouc-Wen, trilinear, stiffness degrading, Kent-Scott-Park concrete, tension stiffening concrete, and Giuffr´e-Menegotto-Pinto steel material models. The element library currently includes linear-elastic beam-column, elastic spring (experimental), inelastic plastic hinge, nonlinear panel-zone, nonlinear strength and stiffness deterioration, displacement-based fiber beam-column, force-based fiber beam-column, zero-length, and nonlinear dummy (for P-Delta effect) elements.

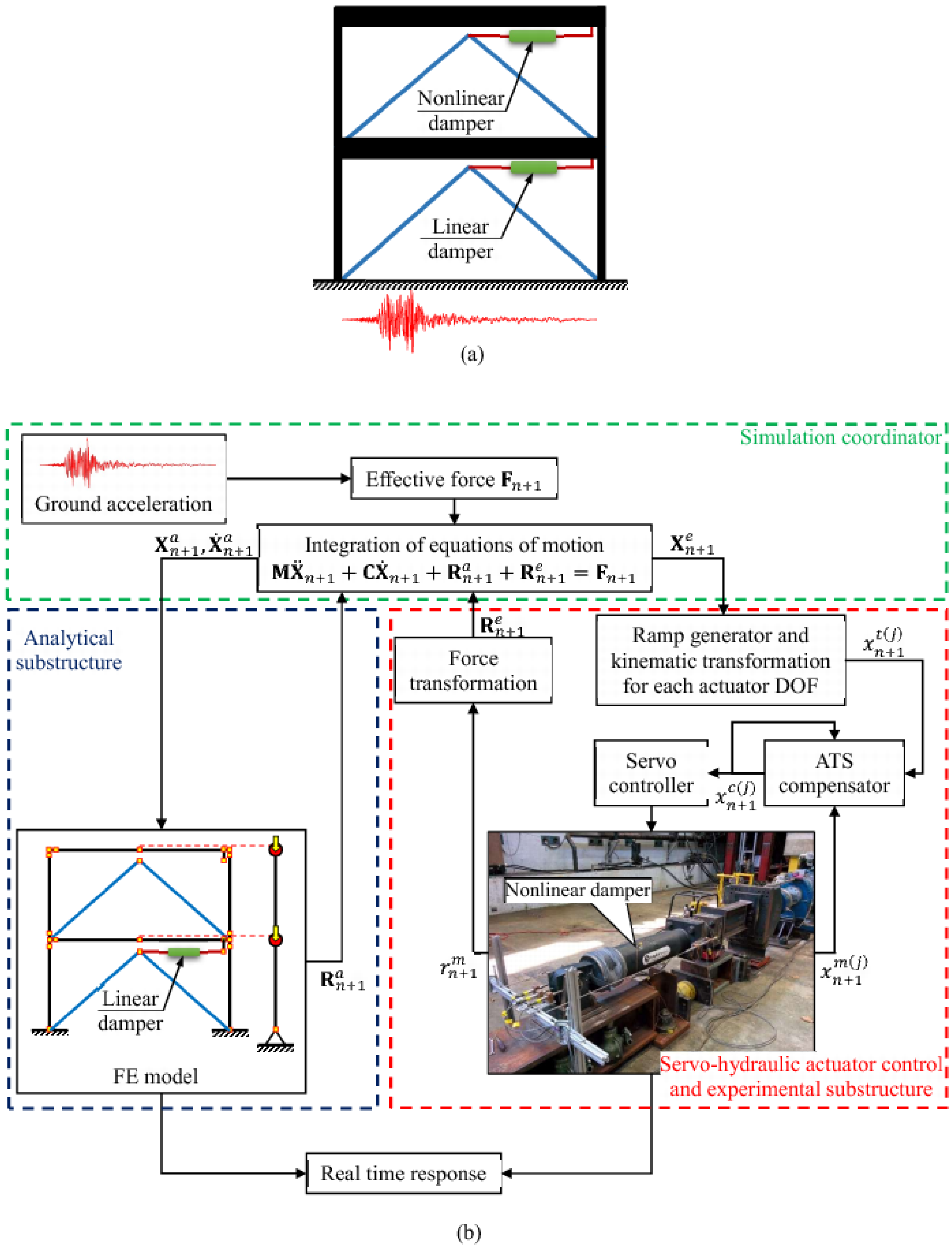

Figure 2-2 Real-time hybrid simulation: (a) example structural system subjected to seismic excitation, and (b) schematic representation of real-time hybrid simulation for the example structural system (Kolay, 2016).

2.2.3 Servo-Hydraulic Actuator Control and Experimental Substructure

This module is responsible for receiving the displacement command $\mathbf{X}_{n+1}^{e}$ and providing the experimentally measured restoring forces $\mathbf{R}_{n+1}^{e}$. As shown in Figure 2-2 (b), this module consists of several components which are explained below.

2.2.3.1 Ramp Generator and Kinematic Transformation

In an RTHS, the integration time step size Δt used must be greater than or equal to the sampling period δt of the digital servo controller that is used to control the servo-hydraulic actuators. The servo-controller runs at a sampling rate of 1024 Hz, that is, $\delta t = 1/1024$ sec. Furthermore, to ensure smooth and continuous movement of the servo-hydraulic actuators, Δt is chosen to be an integer (J) multiple of δt, that is, $\Delta t = J\delta t$, and the command displacements $\mathbf{X}_{n+1}^{e}$ are ramped using a ramp generator. Typically, a linear ramp generator is used because of its simplicity and ease of implementation. The ramped displacement for the jth substep of the $(n+1)$th time step, that is, at time $t_{n+1}^{(j)} = (Jn + j)\delta t$, is determined as follows:

$$\mathbf{X}_{n+1}^{e(j)} = \mathbf{X}_{n}^{e} + \frac{j}{J}(\mathbf{X}_{n+1}^{e} - \mathbf{X}_{n}^{e}) \tag{2.6}$$

where $j \in \{1,2,\dots,J\}$. $\mathbf{X}_{n+1}^{e(j)}$ is then transformed to each actuator DOF based on a kinematic transformation as required. Thus, the target displacement for each actuator DOF, denoted as $x_{n+1}^{t(j)}$, is obtained. The term 'target' indicates that this displacement is targeted to be achieved at the associated specimen DOF after the deformation of the specimen. In other words, it is targeted that the specimen measured displacement at the associated DOF, denoted as $x_{n+1}^{m(j)}$, be equal to $x_{n+1}^{t(j)}$.

2.2.3.2 Adaptive Time Series (ATS) Compensator

The dynamics of the combined servo-hydraulic system and the experimental substructure inevitably causes a time delay and a change in amplitude of the actual achieved specimen displacement. Furthermore, the amount of time delay and amplitude error can potentially vary throughout the simulation. Numerous compensation techniques (e.g., Chen and Ricles,2009, 2012; Chae et al., 2013; Phillips et al., 2013) have been developed in the past that modify the input actuator displacement so as to reduce the difference between the target displacement $x_{n+1}^{t(j)}$ and measured specimen displacement $x_{n+1}^{m(j)}$. Amongst these, the second-order adaptive time series (ATS) compensator developed by Chae et al. (2013) is found to work well and has been used recently by numerous researchers at the RTMD facility and elsewhere. The compensator uses the measured specimen displacement x^{m} as well as the velocity and acceleration based on x^m as a feedback to determine the adaptive compensation coefficients at each substep j (see Equation (2.6)) based on the data over a previous $q\Delta t$ duration of time, where q is a user defined input. Typically, $q\Delta t = 1$ sec is used. Using these adaptively determined coefficients, the compensated displacement is determined for each actuator The details and implementation procedure of the compensator is not presented here and can be found in Chae et al. (2013).

2.2.3.3 Servo Controller

The servo controller receives the compensated displacement command, communicates with all the servo-valves, actuators, transducers, hydraulic service manifold (HSM) control box, and applies the command to the hydraulic actuators. The details of the servo-controller available at the facility were presented earlier in Section 1.3.5.

2.2.3.4 Servo-Hydraulic System and Experimental Substructure

The servo-hydraulic system which includes the dynamic actuators and hydraulic power supply system enables the application of the command displacement on the experimental substructure within the time duration of the ramp function. The RTMD facility has five large capacity dynamic actuators (see Section 1.3.2) with a stroke range of ± 500 mm, two of the actuators have a force capacity of ± 2300 kN and the remaining three have a force capacity of ± 1700 kN at 20.7 MPa (3000 psi) hydraulic pressure. Figure 1-2 shows the hydraulic power envelope curves for the aforesaid two types of actuators. Each actuator is ported for three servo-valves. The maximum velocity that can be achieved by the 2300 kN and 1700 kN actuators are 840 mm/s and 1140 mm/s, respectively, (see Figure 1-2) when three servo-valves are placed on the actuators. Each servo-valve has a maximum flow capacity rate of 550 gpm at a hydraulic supply pressure of 20.7 MPa (3000 psi) (see Section 1.3.3). The hydraulic power supply system consists of 5 pumps, each with a flow rate capacity of 450 lpm (120 gpm), and 16 piston accumulators connected to 9 gas bottles, each piston with 190 liters (50 gallons) of flow and each gas bottle with 1;325 liters (350 gallons) of Nitrogen (see Section 1.3.1). This configuration enables RTHS of a four-story (4-actuators) 0.6-scale frame structure to be performed with a typical earthquake record for a duration of 30 sec with the supply pressure maintained between 20.7 to 24.1 MPa.

As noted earlier, the experimental substructure is the component of the hybrid system that cannot be modeled analytically and is modeled physically in a laboratory with the appropriate boundary conditions. As the actuators impose the command displacement on the specimen, the actuator load cells simultaneously measure the restoring forces at each substep. These restoring forces are transformed to the global structure DOFs using a force transformation. If the measured restoring forces $\mathbf{R}_{n+1}^{e}$ is fed back after each specimen DOF reaches the target displacement $x_{n+1}^{t(J)}$, a delay equal to the sampling time δt is introduced in the calculation for the next time step. To avoid this delay, often referred to as the 'communication delay', an extrapolation technique (Chen et al. 2009; Kolay et al. 2015) can be adopted using the stiffness $\mathbf{K}^{e}$ and supplemental damping $\mathbf{C}^{e}$, if any, matrices of the experimental substructure as follows:

$$\mathbf{R}_{n+1}^{e} = \mathbf{R}_{n+1}^{m(J-1)} + \mathbf{K}^{e}\left[\mathbf{X}_{n+1}^{e} - \mathbf{X}_{n+1}^{e(J-1)}\right] + \mathbf{C}^{e}\left[\dot{\mathbf{X}}_{n+1}^{e} - \mathbf{V}_{n+1}^{e(J-1)}\right] \tag{2.7}$$

where $\mathbf{R}_{n+1}^{m(J-1)}$ is the measured restoring force vector corresponding to the imposed displacement $\mathbf{X}_{n+1}^{e(J-1)}$; $\mathbf{V}_{n+1}^{e(J-1)}$ is the velocity of the ramp generator in Equation (2.6); and the other parameters are as defined earlier. Theoretically, the most accurate results would be obtained if the tangent stiffness and damping matrices are used in Equation (2.7). However, these tangent matrices are difficult to measure and not readily available in an RTHS using an explicit integration algorithm. For a single elastomeric damper as the experimental substructure, Chen et al. (2009) studied the influence of $\mathbf{K}^{e}$ and $\mathbf{C}^{e}$ on the RTHS results considering three extreme cases: (i) extrapolation using initial stiffness and damping, (ii) extrapolation using initial stiffness only, and (ii) no extrapolation. They showed that the test results are not sensitive to this extrapolation, since the sampling time $\delta t = 1/1024$ sec is small. A similar study was carried out by Kolay et al. (2015) which involved RTHS of a three-story 0.6-scale prototype steel frame building, and it was shown that the results are not sensitive for the same aforesaid reason. Therefore, typically the extrapolation in Equation (2.7) can be omitted.

2.3 Distributed Hybrid Simulation

In distributed hybrid simulation (DHS), physical substructures are located at different geographical locations (i.e., experimental test facilities), with the analytical substructure located at either one of the experimental sites or at an independent site, as illustrated below in Figure 2-3. DHS thereby enables the capabilities of several experimental facilities and a computational facility to become engaged in the test. Figure 2-3 is a schematic describing the three sites that were involved in the NEES MiniMost experiment (Pearlman, et al. 2004), where the University of Illinois at Urbana, Champaign and the University of Colorado at Boulder participated as experimental sites, and National Center for Supercomputer Applications (NCSA) participated as a computational site. As shown in Figure 2-3, an experiment coordinator coordinates the test, using the Internet to receive control commands from the computational site, and then sending via the Internet each of the experimental sites their command displacement to be imposed to their physical substructure for a given time step. The simulation coordinator receives back from each experimental site via the Internet the restoring forces corresponding to each physical substructure. In the MiniMOST experiment, the NTCP protocol was used for communication between the coordinator and the sites.

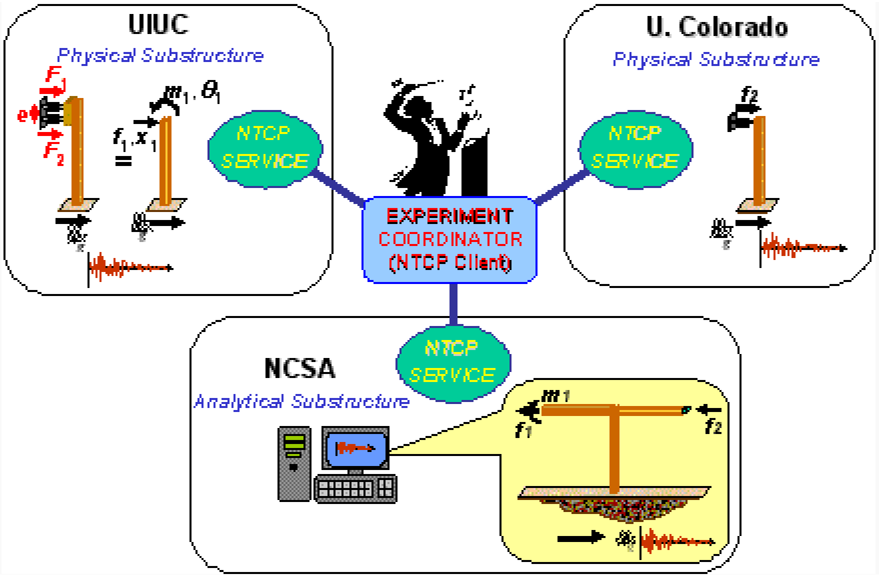

Figure 2-3 Distributed hybrid PSD testing: NEES MiniMOST experiment (Pearlman, et al. 2006)

The RTMD earthquake simulation facility can participate in distributed HS testing with any computational or experimental facility that has the NTCP protocol. Figure 1-12 shows a schematic of the servo-hydraulic control and IT systems for the RTMD earthquake simulation facility. When a distributed HS is performed, communication with each remote site is established through the NTCP protocol. When the RTMD earthquake simulation facility participates as an experimental site, the command received from a remote experiment coordinator is authenticated on the RTMDtele, and then passed to the RTMDsim (see Figure 1-12 for the servo-hydraulic control and IT systems schematic). RTMDsim evaluates the command for conformance with equipment limits (e.g., maximum actuator forces, actuator maximum displacements), before transferring it to the Controller via the RTMDxPC and SCRAMNet. The Controller has active limits set in RTMDctrl before the test begins. These active limits are enforced as the command is received.

2.4 Effects of Multi-directional DOFs

A variety of challenges arise when kinematics of the motion of the test specimen influences the actuators and instrumentation. A simple example is given in Figure 2-4 Geometrical inaccuracies due to test structure kinematics, where x and y displacements of the test structure, shown in plan view, are controlled by the three actuators. The displaced configuration of the test structure results in transverse movement of the actuators and measurement sensors, introducing an error in the correct positioning of the specimen by the actuators and measurement sensors. The position of the test structure, actuators, and measurement devices must be accounted for during each time step of a test, using a kinematic correction procedure to ensure accurate test results.

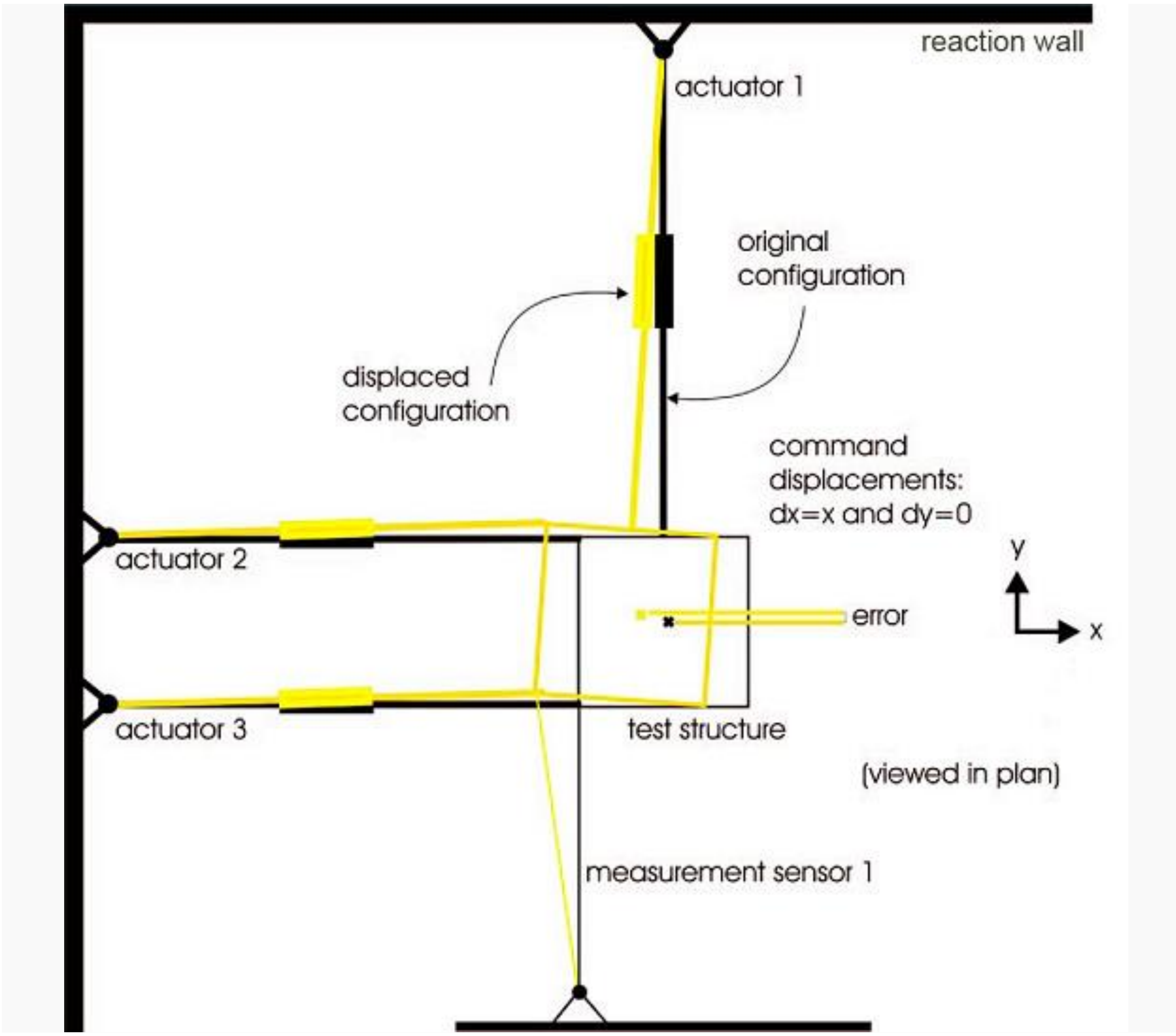

Figure 2-4 Geometrical inaccuracies due to test structure kinematics

The algorithm for multi-directional testing at the RTMD earthquake simulation facility includes a kinematic correction scheme, where the position of the test structure, actuators, and measurement devices is tracked during a test. For the general case involving 3-D motion, a total of eight displacement sensors (S1 through S8) are required to be arranged, as shown in Figure 2-5, where a rigid loading block is used in the test to control the degrees of freedom at the SPN (Structural Physical Node) shown. The instrumentation is attached to the structure at measurement structural nodes MSN1 and MSN2.

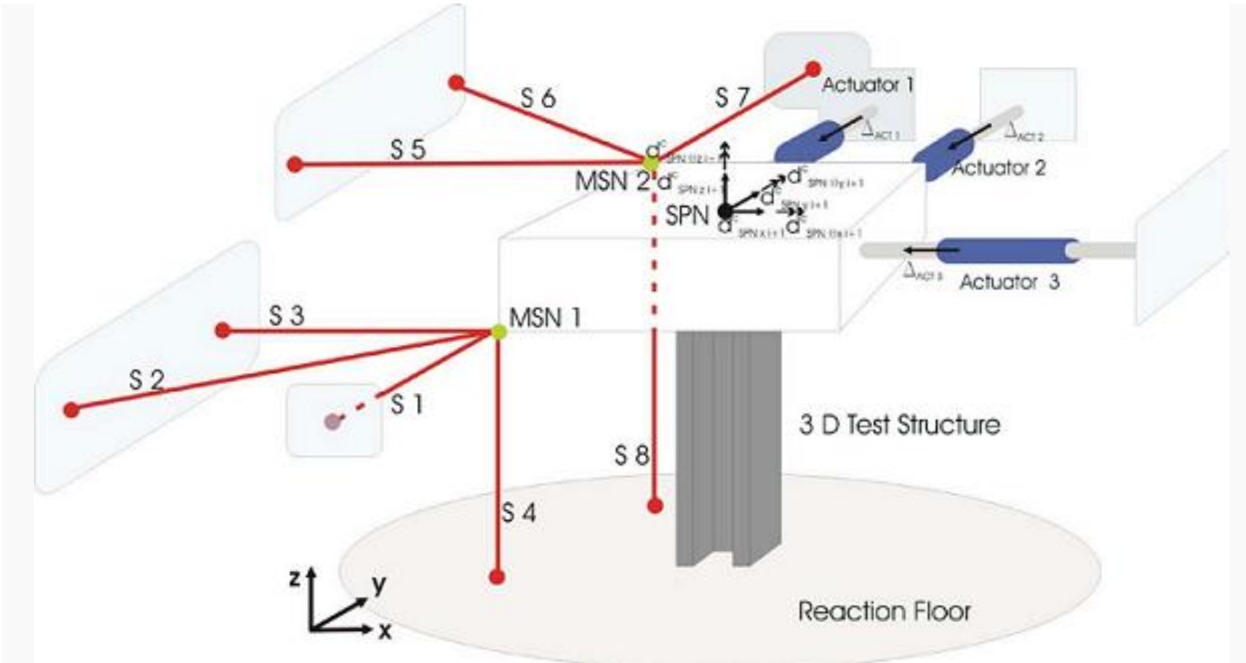

Figure 2-5 3-D test with displacement sensors arranged for tracking specimen position

The kinematic correction consists of the following steps:

(1) The extension or contraction ΔACT_j of each of the actuators j involved in the test is determined based on the command displacement $d_{\mathrm{SPNP}_{i+1}}^{c(k+1)}$ to be imposed on the structure at the SPNp controlled by the actuators, where:

$$\Delta_{\mathrm{ACT}_j} = f\left(d_{\mathrm{SPNP}_{i+1}}^{c(k+1)}, X_{\mathrm{SPN_P}}^{0}, X_{\mathrm{SPN_P}}^{d}, X_{\mathrm{ASN}_j}^{0}, X_{\mathrm{ASN}_j}^{d}\right) \tag{2.8}$$

In Equation (2.8), $f(\cdot)$ is a function that relates the extension or contraction of actuator j to the kinematics of the motion of the SPN, whose displacements are a subset of which contains the command displacements of all of the SPNs in the test structure. This function has as independent variables the command displacement to be imposed to the SPN, $d_{\mathrm{SPNP}_{i+1}}^{c(k+1)}$; the coordinates of the SPN in the undeformed geometry, $X_{SPN_P}^{0}$; the coordinates of the SPN in the deformed geometry, $X_{SPN_P}^{d}$; the coordinates of the actuator nodes (a node is defined at each end of the actuator) of actuator j in the undeformed geometry, $X_{\mathrm{ASN}_j}^{0}$; and the coordinates of the actuator nodes of actuator j in the deformed geometry, $X_{\mathrm{ASN}_j}^{d}$.

(2) As each of the actuators extends or contracts in accordance with Equation (2.8), the motion of each SPN, corresponding to the measured displacement is determined, where for SPNp the measured motion $d_{\mathrm{SPNP}_{i+1}}^{m(k+1)}$ corresponding to the displacement measurements is:

$$d_{\mathrm{SPNP}_{i+1}}^{m(k+1)} = f\left(X_{\mathrm{SPN_P}}^{0}, X_{\mathrm{MSN1}}^{0}, X_{\mathrm{MSN2}}^{0}, X_{\mathrm{MSN1}}^{d}, X_{\mathrm{MSN2}}^{d}\right) \tag{2.9}$$

In Equation (2.9), $f(\cdot)$ is a function that relates the motion of SPNp to the displacement transducer measurements for SPNp. This function has as independent variables the coordinates of the SPN in the undeformed geometry, $X^0_{\mathrm{SPN_P}}$; the coordinates of MSN1 in the undeformed geometry, X^0_{MSN1}; the coordinates of MSN2 in the undeformed geometry, X^0_{MSN2}; the coordinates of MSN1 in the deformed geometry, X^d_{MSN1}; and the coordinates of MSN2 in the deformed geometry, X^d_{MSN2}.

(3) The measured restoring forces at SPNp during substep k are:

$$r^{m(k+1)}_{\mathrm{SPN}_{\mathrm{P}_{i+1}}} = f\left(X^d_{\mathrm{SPN_P}}, X^d_{\mathrm{ACT(i,m)}}, P_{\mathrm{ACT(i,m)}}\right) \qquad (2.10)$$

Where in Equation (2.10), $f(\cdot)$ is a function that relates the restoring forces at SPNp to the load cell reading of the actuators associated with controlling the motion of SPNp. This function has as independent variables the coordinates of SPNp in the deformed geometry, $X^d_{\mathrm{SPN_P}}$; the coordinates of the nodes of the actuators in their deformed geometry, $X^d_{\mathrm{ACT(i,m)}}$, that are associated with SPNp; and the load cell reading of the actuators, $P_{\mathrm{ACT(i,m)}}$, associated with SPNp.

The above functions in each of Equation (2.8) through (2.10), are developed on a case by case basis, and dependent on the geometry of the loading apparatus and stiffness. These functions are subsequently programmed as a module by the staff of the RTMD earthquake simulation facility, which is integrated into the control algorithms (on the RTMDxPC) to account for the kinematics of a test structure. The kinematic correction can be done based on either the incremental command displacements or the command of total displacements to each SPN in the test structure.

2.5 RTMD Control System and IT System Architecture

A schematic of the servo-hydraulic control and IT systems for the RTMD earthquake simulation facility was presented in Figure 1-12. The RTMD real-time testing architecture features a Real-Time Integrated Control System for real-time testing. Algorithms that enable real-time testing reside on the RTMDxPC, which is a dedicated real-time xPC kernel. These algorithms enable real-time hybrid simulation. Multi-directional kinematics is accounted for by algorithms that also reside on the RTMDxPC or RTMDsim. All of the algorithms are implemented using Matlab and Simulink from MathWorks, Inc. and are compiled onto the RTMDxPC for real-time testing. Lesser used options are to develop custom JAVA or MATLAB programs, C++ modules or LabVIEW VIs. The Real-Time Integrated Control System is created by using SCRAMNet to enable communication among the telepresence server (RTMDtele), real-time target PC (RTMDxPC), the servo-hydraulic controller (RTMDctrl), and data acquisition system (RTMDdaq). The data exchange across SCRAMNet occurs within 190 nanoseconds per channel, essentially enabling share memory among the workstations, including the servo-hydraulic controller and the RTMDxPC, thus enabling real-time testing capabilities. Synchronization is maintained through the use of a pulse trigger placed on SCRAMNet by the

RTMDctrl at the rate of 1024Hz. A data structure for SCRAMNet is in place that includes multiple states for commands and feedback signals, enabling advance servo-hydraulic control laws to be implemented and sophisticated testing methods to be performed.

For a real-time hybrid simulation, numerous options exist for modeling the analytical substructure. The preferred and primary method is to develop models with Simulink to describe the analytical substructure. The integrated control system has a hydraulics-off simulation mode for use in validation of testing methods, training, and education. In the hydraulics-off simulation mode, the servo-hydraulic equipment (e.g., actuators, servo-valves) and test structure are analytically modeled. Models of the servo-hydraulic equipment have been developed in Simulink for this purpose, and have been calibrated based on system identification tests of the equipment (Zhang et al. 2005) To ensure the safety of personnel and equipment during a test, software limits are enabled on the RTMDxPC and RTMDctrl; hardware piston stroke limit switches are placed on the actuators and an emergency stop system is activated throughout the laboratory. The Real-Time Integrated Control System can also be operated to participate in a distributed hybrid simulation. Other tested programs and software environments which can be used include UI-SimCor, ANSYS, and OpenFresco with OpenSEES.

2.6 Requirements for Users of the RTMD facility

Researchers developing a proposal to use the NHERI Lehigh RTMD EF need to know the demand that their tests will impose on the equipment in order to ensure the equipment capacity of the facility is not surpassed. This will help to ensure that the test can be successfully completed. Equipment specifications were summarized in Section 1.3 of this guide. It is recommended that researchers planning tests at the NHERI Lehigh RTMD facility consider the following:

1. Researchers must be aware that the maximum velocity that an actuator can achieve depends on the concurrent force in the actuator (i.e., hydraulic actuator power). Perform as accurate as possible time history analysis of the candidate test structure (nonlinear analysis may be needed) using the forcing function expected to be used during the test. Plot the ensuing force-velocity orbits associated with an actuator degree of freedom. Compare these orbits with the hydraulic actuator power envelop provided in Section 1.1 (see Figure 1-2) of this guide to check that the actuator power capacity is not surpassed, and that forces at the tie down points for the actuators and reactions of the test structure do not surpass their capacity (see Section 1.2.2), as well as the overturning moment capacity of the ATLSS multi-directional reaction wall.
2. From the time history results, determine the stroke range required of actuators and instrumentation, and check that the demand does not surpass the capacity summarized in Section 1.3.

3. If necessary, scale-down the test structure to avoid having the demand in (1) and (2) exceed the capacity of the equipment and instrumentation.

After the project is funded by the sponsor, the researchers will need to work with the research staff of the NHERI Lehigh RTMD EF to finalize the details of the test structure. This will include running the hydraulics off mode software to verify the demand on the equipment and instrumentation, as well as the functionality of any modifications made to the standard testing protocols in use at the NHERI Lehigh RTMD EF (e.g., using a new direct integration algorithm defined by the researcher). More information on the hydraulics off software will be provided at scheduled RTMD training sessions.

2.7 Software Policies

The Real-Time Integrated Control System enables the real-time control of high speed, large capacity hydraulic actuators. These actuators pose a danger if not operated correctly because of user error or software generating incorrect actuator commands. It is the policy of the facility, that in order to ensure the safety of the laboratory and prevent damage to equipment, software used for any form of testing at the NHERI Lehigh RTMD EF must be validated before placed on the Real-Time Integrated Control System. The algorithms which the software is based on must be shown to be stable. The user desiring to place the software on the Real-Time Integrated Control System must provide documented proof that the software has been validated and the algorithm is stable. The approval of the implementation of the software onto the Real-Time Integrated Control System will be at the discretion of the staff of the NHERI Lehigh RTMD EF to ensure the safety of the laboratory and equipment. It is strongly recommended that users make use of the existing software available on the Real-Time Integrated Control System in lieu of user developing their own software that requires validation and stability studies. A list of software for hybrid simulation available at the RTMD is given in Table 2-1.

Table 2-1 NHERI Lehigh Simulation Software

Software	Version	Web Link for Documentation	Funding Agency	Availability
Matlab & Simulink	R2015b	http://www.mathworks.com/products/matlab/	NA	On-site license
Simulink RT Target	R2015b	http://www.mathworks.com/products/simulink-real-time/	NA	On-site license
OpenSEES	2.5	http://opensees.berkeley.edu/	NSF	Open source
OpenFresco	2.6.2	http://openfresco.berkeley.edu/	NSF	Open source
HybridFEM	5.0	http://www.rtmd.lehigh.edu/wordpress/uploads/reports/HybridFEM-2D_4.2.4_Users_Manual.pdf	PITA	In executable form
RDV	2.2.2	http://www.rtmd.lehigh.edu/wordpress/resources/rdv	NSF	Open source
Data Turbine	3.1a	http://dataturbine.org/	NA	Open source
Lehigh Data Model	n/a	http://www.rtmd.lehigh.edu/resources/lehigh-data-model	PITA	Open source
Inverse Compensation for Actuator control	n/a	http://www.rtmd.lehigh.edu/wordpress/uploads/reports/ASCE_Chen_Tracking_Error-Based_AIC_for_RT_testing.pdf	PITA; NEES O&M	Open source
Adaptive Inverse Compensation for Actuator control	n/a	http://www.rtmd.lehigh.edu/wordpress/uploads/reports/ASCE_Chen_Tracking_Error-Based_AIC_for_RT_testing.pdf	PITA; NEES O&M	Open source

Notes:
NA: Software developed by vendor
PITA: Pennsylvania Department of Community and Economic Development through Pennsylvania Infrastructure Technology Alliance
NSF = National Science Foundation

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3 Telepresence Capabilities

3.1 LAN Equipment and Computer Network

Shown below is a floor plan of the laboratory of the NHERI Lehigh RTMD EF, where the local area network (LAN) is identified. The laboratory of the NHERI Lehigh RTMD EF is supported by a switched gigabit copper network comprised of 16 independent connection ports on the laboratory floor, and an additional 8 connections in the control room to accommodate the control network, data acquisition, and RTMD servers. This network is operated as an independent subnet within the NHERI Lehigh RTMD EF, isolated from common network traffic, and managed as a secure subnet. The laboratory and control room network are connected through a managed gigabit switch to the university's main backbone. From the NHERI Lehigh RTMD EF switch through the campus backbone all traffic travels over gigabit fiber connections. All the network equipment is managed and monitored by Lehigh University's Library and Technology Services.

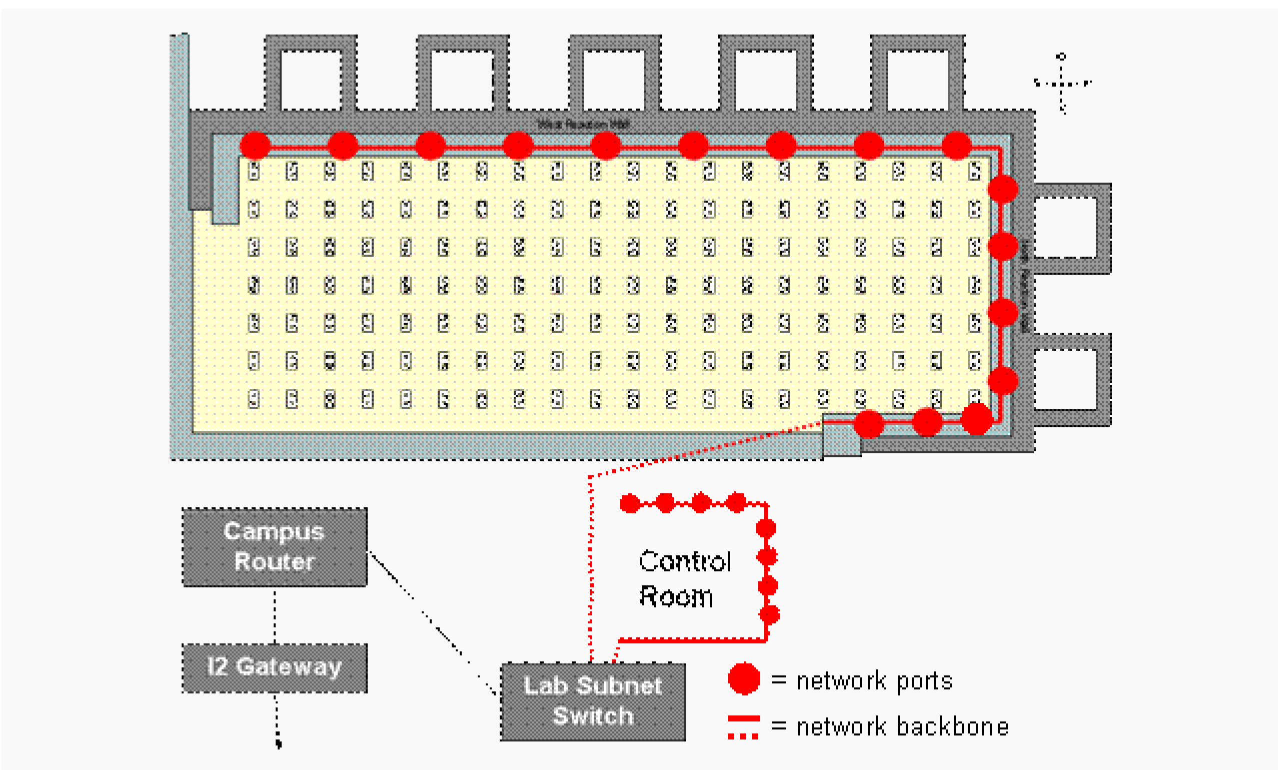

Figure 3-1 Local Area Network of the RTMD earthquake simulation facility

With the network isolated from the office network and the corresponding daily traffic, this allows greater flexibility and a larger pool of network addresses from which to assign computers, advanced sensors, and network cameras addresses, while making the maximum bandwidth available to the experimental and telepresence systems. The network switch allows the RTMD IT system to operate a VLAN for security purposes and effectively shield systems controlling the experiment from the outside world.

For on-site (local) participants, several network ports have been provided in the control room for laptops and portable computers. A wireless network and the general building 1 gigabit network are available in this room for observers. Security on the wireless access point is enabled and arrangements for wireless access need to be obtained at the time of a visit to the NHERI Lehigh RTMD EF.

In addition to the equipment of the IT system described in Section 1.4, the system has several additional pieces of equipment. Network cameras are accessible through web interfaces on the RTMDws system. Direct network access to these cameras is restricted in order to achieve optimal video streaming and ensure camera controls are not tampered with. As part of this network there are eight HD web cameras for laboratory use, four of which are high definition pan-tilt-zoom Sony SNC-EP550 and the remaining four are standard definition pan-tilt-zoom Sony SNC-RZ30N, all having portable mounts for use in the laboratory. Video streams are managed through the telepresence system using Blue Iris. Additional still cameras are available for use in the laboratory on a use fee basis at this time.

Two overhead video monitors exist in the control room, and are configured and maintained with real-time data and video content from active experiments. Local and remote participants will be able to view the displays via the network.

3.2 Telepresence

3.2.1 General

Applications developed for use by experimental participants in the configuration of data acquisition, simulation, and control will be discussed in further detail at the end of this chapter. This includes applications and detailed instructions for use of the software for configuration of data and video streaming and remote experimental participation.

3.2.2 DataTurbine (RBNB)

DataTurbine® is a software server that provides a ring buffered network (RBNB) as a data path between suppliers and consumers of both static and dynamic information. Diverse distributed applications pool and share data using DataTurbine as a common intermediate point of contact. DataTurbine manages all aspects of inter-application data traffic, assimilating data acquisition and storage into the network itself.

The RTMD IT infrastructure implements a DataTurbine server on RTMDtele and sources it with data from RTMDdaq, RTMDsim, RTMDxPCs and RTMDctrl via the SCRAMNet. A custom application exists which allows the administrator of the DataTurbine server to determine the rate the data is received off of the SCRAMNet, the rate the data is flushed across the network at and the size of the stored data archive.

Figure 3-2 DataTurbine Architecture

3.2.3 Real-time Data Viewer (RDV)

The Real-time Data Viewer (RDV) provides an interface for viewing and analyzing live or archived time-synchronized data and video either locally or streamed across a network from a DataTurbine (RBNB) server. RDV is capable of displaying textual and numerical data, still images, and video. Users of RDV can access the RTMD DataTurbine server on an Internet-connected system running Java. This included Windows, Linux and Mac OSX systems. The features of RDV are listed below, including the 3D Model Panel developed at the RTMD facility.

- Synchronous display of numeric, textual, still images, and video data
- Monitor experimental data in real-time or playback from history at increased rates
- 2D time series or XY data plots
- Support for high- or low-resolution still-image and video data
- Multiple pages of data panels
- 3D visualization capability
- Support for visualization of large data sets (>1M samples)

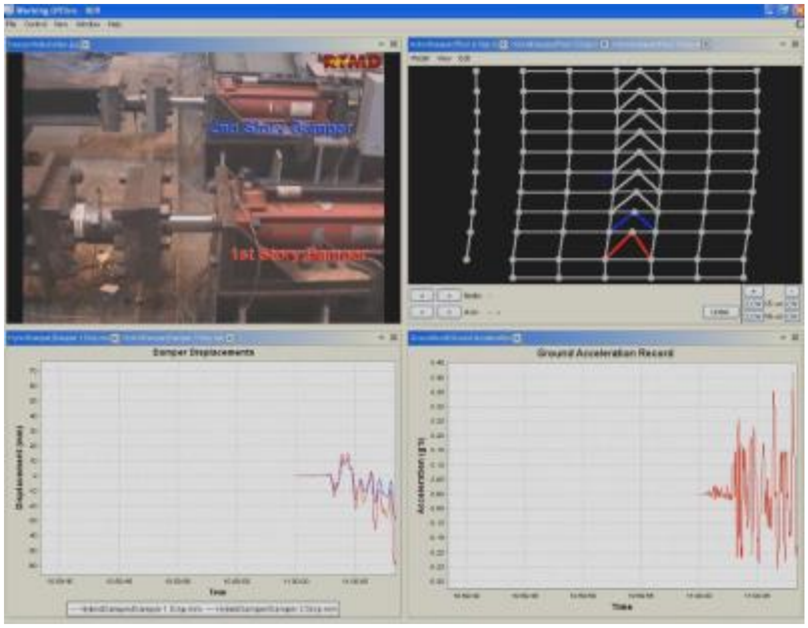

Figure 3-3 Screen capture of RDV showing live video, 3D model and plotting data

3.2.4 Blue Iris Web Camera Server

Blue Iris Web Camera Server is used to stream and archive digital video recorded through web cameras. Users have the ability to:

- Remotely connect from anywhere in the world from any web enabled device.
- View live cameras and recorded clips.
- Be authenticated with permission based viewing.
- Have access to Pan-Tilt-Zoom functionality remotely.

4 Education and Outreach

4.1 General

The vision of the Education, Outreach, and Training (EOT) program at NHERI Lehigh RTMD EF can be outlined as follows:

1. Educate and inform a diverse audience at all levels and attract young individuals into science, technology, and engineering to a broad audience, including students (K-12, undergraduate, graduate) and professionals (practitioners, researchers, professors) through the utilization of NHERI Lehigh RTMD EF equipment, technology, and staff.
2. Enhance the awareness and utilization of NHERI Lehigh RTMD EF for performance-based natural hazards engineering research.

The following section will illustrate the activities implemented by NHERI Lehigh RTMD EF staff to support its EOT vision.

4.2 Example Activities

4.2.1 Education

4.2.1.1 University Curriculum

The undergraduate and graduate teaching in Civil and Environmental Engineering (CEE) will be integrated into the activities of the NHERI Lehigh RTMD EF through curriculum. Numerous undergraduate and graduate courses have been augmented or developed to include subjects and/or experiments related to NHERI activities. Such courses, along with whom they were offered, are provided below:

Undergraduate curriculum

- CEE 159 “Structural Analysis I”, Instructor
- CEE 211 “Research Problems”, Instructor
- CEE 242 “Geotechnical Engineering”, Muhannad Suleiman
- CEE 244 "Foundation Engineering", Sibel Pamukcu
- CEE 258 “Structural Laboratory”, Stephen Pessiki
- CEE 259 "Structural Analysis II", James Ricles
- CEE 352 "Structural Dynamics", Richard Sause
- CEE 361 “Bridge System Design”, Instructor
- CEE 363 "Building Systems Design", James Ricles

Graduate curriculum

- CEE 406 “Structural Reliability of Components and Systems”, James Ricles
- CEE 415 “Analysis and Design of Ductile Steel Systems”, James Ricles
- CEE 419 "Structural Behavior Laboratory", Stephen Pessiki
- CEE 441 “Dynamic Analysis in Geotechnical Engineering”, Instructor
- CEE 453 “Nonlinear Analysis of Structural Components and Systems”, James Ricles
- CEE 455 "Advanced Structural Dynamics", Richard Sause
- CEE 456 "Behavior and Design of Earthquake Resistant Structures", Peter Mueller
- CEE 467 “Advanced Topics in Structural Engineering", Shamim Pakzad

4.2.1.2 University Classroom Projects/Activities

Lehigh University has incorporated the natural hazards engineering discipline into several classroom projects/activities as part of semester curriculum for courses. Examples of the projects are provided below:

Seismic Testing of Model TV Tower

Under the direction of Professor Yungfeng Zhang, undergraduate (freshmen) students at Lehigh University participated in the design and creation of Model TV Towers that were subjected to subsequent testing on a shake table to understand structural performance under earthquake conditions. The course title is Engineering 5, "Introduction to Engineering Practice". This project was included as part of the course requirements during both the Fall 2005 and Spring 2006 semesters.

Seismic Testing of Pagoda Tower

Under the direction of Professor Yungfeng Zhang, students at Lehigh University participated in the design and creation of a Pagoda Tower that were subjected to subsequent testing on a shake table to understand structural performance under earthquake conditions. The goal of the project was to experimentally study the seismic behavior of a Japanese pagoda and base-isolation technology. Students in the course built a scaled version of the 5-story Japanese wood pagoda. The testing was held on April 24, 2006. The Course Title is CE 467-41, "Smart Structural Systems".

4.2.1.3 Research Experience for Undergraduates Program

NHERI Lehigh RTMD EF staff has vast experience operating Research Experience for Undergraduate (REU) programs, which provide undergraduate students with exposure to research projects in the laboratory. While operating its NEES equipment facility from 2004 through 2014, RTMD staff annually operated a NEES-funded REU Program exposing participating students to NEES research projects that were active during that period. The NEES RTMD Equipment Site operated the NEES REU program in conjunction with a summer REU program based out of the ATLSS Engineering Research Center, the latter of which was funded in part by a grant from the Commonwealth of Pennsylvania, Department of Community and Economic Development through its Pennsylvania Infrastructure Technology Alliance (PITA) program. The number of participating students generally ranged from 5 to 10 students per year.

An overview of the NEES REU programs is provided below for reference. If funding becomes available, It is expected that a NHERI-funded REU program would operate under a similar structure.

Example REU Program Overview

As part of the program, undergraduate students from various universities and colleges spent 10 weeks conducting research under the direction of Lehigh University faculty and staff at the ATLSS Engineering Research Center, within which Lehigh RTMD Equipment Site was located. The NEES students conducted research in the area of earthquake engineering, while the ATLSS students researched under a broader Civil and Structural Engineering research area. At the conclusion of the program, students were required to submit a technical report and give a presentation on their findings. Additionally, throughout the program, the students participated in a series of workshops to enhance their professional skills and partook in a series of offsite tours that exposed the students to industrial environments. A typical REU program included the following workshops and tours:

Example Workshops

1. ATLSS Safety Presentation/Laboratory Tour, presented by ATLSS staff
2. Laboratory Safety/Construction Safety, presented by Lehigh University Environmental Health and Safety Department
3. Library Search Training, presented by Lehigh University Library and Technology Services Department
4. Resume Building Workshop, presented by Lehigh University Career Services Department
5. Effective Presentations/Powerpoint Workshop, presented by Lehigh University Media Services DepartmentTechnical Report Workshop, presented by ATLSS staff

Example Tours

1. Susquehanna River Bridge
2. Dorney Park
3. High Steel Structures, Inc.
4. Carpenter Technology Corporation

4.2.2 Outreach

4.2.2.1 K-12 Activities

NHERI Lehigh RTMD staff has participated in several K-12 activities, targeted at supporting the site vision of promoting the earthquake engineering discipline to students, while operating the aforementioned NEES program. Any school districts, community programs, youth organizations, camps, etc. interested in discussing potential outreach programs available for their students through the NHERI Lehigh RTMD EF are encouraged to contact the NHERI Lehigh RTMD EF Operations Manager, whose contact information is provided in Section 4.3. Examples of K-12 activities that occurred during the NEES operational period are provided below:

S.T.A.R. Academies

NEES RTMD staff hosted Lehigh University S.T.A.R. (Students That Are Ready) Academies students. S.T.A.R. Academies is an early intervention program designed to enrich and enhance the academic performance of economically and academically disadvantaged and/or at-risk elementary/middle/high school aged children. Student ages varied from 4th through 12th grade, and represented over five school districts (39 schools) in the Greater Lehigh Valley. The primary goals are to prepare and place these students in colleges and universities across the country in STEM and business majors. Activities included the following:

1. General discussion on earthquake engineering
2. Tours of the ATLSS Research Center and RTMD Equipment Site
3. Presentations on earthquakes in Pennsylvania
4. Demonstration of a small-shake table (seismic simulation) system and accompanying instrumentation (accelerometers) to illustrate how earthquake information is recorded
5. Student construction of structures using LEGOs that were subsequently subjected to earthquakes representative of those observed in Pennsylvania, California, and Alaska using a small-scale shake table (seismic simulation) system. Depending on the age group, design criteria were provided to the students.

The goal was to introduce students to earthquakes in Pennsylvania and basic earthquake engineering design considerations while providing a hands-on experience for the students.

Centennial School

NEES RTMD staff hosted Centennial School of Lehigh University students. Centennial School of Lehigh University pursues a two-fold mission: (a) to serve children with disabilities and their families, and (b) to prepare high quality special education teachers and related service personnel to enter the workforce in Pennsylvania and beyond. Centennial School of Lehigh University is a special education day school that serves students, ages 6 through 21, who are classified under the Individuals with Disabilities Act (IDEA) as emotionally disturbed and/or autistic. The activity on this day included a brief presentation on earthquakes in Pennsylvania, followed by the construction of structures using LEGOs that were subsequently subjected to earthquakes representative of those observed in Pennsylvania, California, and Alaska using a small-scale shake table system. The goal was to introduce students to earthquakes in Pennsylvania and provide the students an opportunity to construct a building that will be subjected to earthquakes.

4.2.2.2 Participation at Professional Conferences

NHERI Lehigh RTMD EF faculty and staff participate in various professional conferences related to natural hazards infrastructure engineering. Participation may include, but is not limited to, technical presentations, poster development, proceedings development, and creation of display exhibits.

4.2.2.3 Media Coverage

Activities related to the NHERI Lehigh RTMD EF will be disseminated through various media mechanisms when available. While operating the NSF-funded NEES equipment site, Lehigh RTMD research was highlighted on television news broadcasts, print media, and electronic media. Similar opportunities to highlight the NHERI Lehigh RTMD EF will be identified and implemented. For example, articles related to the launching of the NHERI Lehigh experimental facilities can be found at the following links:

- Lehigh University website: http://www1.lehigh.edu/news/lehigh-wins-5m-natural-hazards-engineering-research
- Lehigh University Department of Civil and Environmental Engineering Website: http://www.lehigh.edu/~incee/news/nheri-award-news.html
- Fierce Government.com website: http://www.fiercegovernmentit.com/story/nsf-launches-experimental-research-facilities-better-understand-impacts-nat/2015-09-28
- AISC Modern Steel Construction Newsletter: http://msc.aisc.org/globalassets/modern-steel/archives/2016/03/news.pdf

4.2.2.4 Participation at Research Workshops

NHERI Lehigh RTMD staff will identify opportunities to assist with the organization of research workshops that help to promote natural hazards infrastructure engineering research. The staff has experience in this area. For example, while operating the NEES equipment site, RTMD staff hosted a workshop entitled "Advances in Real-Time Hybrid Simulation Workshop" in conjunction with the National Science Foundation and the University of Connecticut, School of Engineering. This two-day workshop, held at Lehigh's NEES Equipment Site in Bethlehem, PA, on October 10th and 11th, 2011, was organized in part to disseminate the information and tools for multi-site real-time hybrid simulation and to disseminate information on recent advances in real-time hybrid simulation. The workshop included 56 participants having varying levels of experience with real-time hybrid simulation, and included 16 research presentations related to recent advances in real-time hybrid simulation. The workshop also included 3 demonstrations involving multi-site real-time hybrid simulation, a large-scale frame test, real-time hybrid simulation of MR dampers, and 3 concurrent breakout sessions on real-time computation advances needed in real-time hybrid simulation, servo-hydraulic actuator control for real-time hybrid simulation, and benchmark problems and standardizations for assessing real-time hybrid simulation facilities and results from tests.

4.2.3 Training

4.2.3.1 Seismic Testing Workshop

The NHERI Lehigh RTMD EF will host annual researcher's workshops. The purpose of the workshop is to promote the facility to researchers, encouraging them to use it for their research by undertaking the following tasks:

- Provide participants information about the NHERI Lehigh Experimental Facility capabilities
- Presenting how the NHERI Lehigh Experimental Facility capabilities can enhance your research
- Provide information for preparing NSF proposals which use the NHERI Lehigh Experimental Facility
- Provide the basics of real-time hybrid simulation through lectures and hands-on demonstrations.

An example agenda for the workshop is provided below:

Agenda

Start Time	End Time	Room #	Description	Presenter	Title
8:15 am	8:45 am	B101	Registration and Continental Breakfast	Lehigh EF Staff	-----
8:45 am	8:55 am	B101	Welcome, Objectives, and Agenda Review	James Ricles	Facility PI
8:55 am	9:05 am	B101	Introduction to Lehigh EF Staff and Website	Chad Kusko	ATLSS Admin. Dir.
9:05 am	9:20 am	B101	Overview of NHERI Program and Network	Ellen Rathje	CI PI
9:20 am	10:30 am	B101	NHERI Lehigh Experimental Capabilities and Protocols	James Ricles Tommy Marullo	Facility PI Systems Admin
10:30 am	10:40 am	-----	Break	-----	-----
10:40 am	11:20 am	B101	NHERI Lehigh Facility Project Portfolio	Richard Sause Muhannad Suleiman	Facility co-PI ATLSS Faculty
11:20 am	12:00 pm	H150	NHERI Lehigh Experimental Facility Tour	Peter Bryan	ATLSS IT Mgr.
12:00 pm	1:00 pm	A200	Lunch	-----	-----
1:00 pm	1:30 pm	B101	Guidelines For Proposal Preparation	Chad Kusko	Ops Mgr
1:30 pm	2:00 pm	B101	Real-Time Hybrid Simulation: Background of Theory and Implementation	James Ricles Chinmoy Kolay	Facility PI Research Engineer
2:00 pm	2:20 pm	B101	Distribution of Hands-on Laboratory Exercises (1) Real-Time Hybrid Simulation of Building System; (2) Soil Structure Interaction Pile Test	Chinmoy Kolay Muhannad Suleiman	Research Engineer ATLSS Faculty
2:20 pm	2:35 pm	-----	Break	-----	-----
2:35 pm	4:35 pm	A104 & H150	Hybrid Simulation: Hands-on Participation	Lehigh EF Staff	-----
4:35 pm	5:00 pm	B101	Questions, Closing Remarks, and Evaluations	Lehigh EF Staff	-----

Figure 4-1 Example workshop agenda

4.2.3.2 Website Training

The RTMD staff regularly updates the site training materials offered within the NHERI Lehigh website (http://www.designsafe-ci.org). Certain training modules may be restricted to NHERI Lehigh RTMD staff. Users interested in reviewing training material requiring authorization are encouraged to contact the Lehigh NHERI RTMD EF IT Manager.

4.3 EOT Coordinator Contact Information

The NHERI Lehigh RTMD EF welcomes the opportunity to educate the community on natural hazards infrastructure engineering, develop outreach activities which involve the community, and train the community on how to best utilize the technical capabilities of the site. If you are interested in any of the activities noted above, or have an idea for an activity that you would like to discuss further with RTMD staff, contact the NHERI Lehigh RTMD EF Operations Manager at:

Dr. Chad Kusko, phone: 610-758-5299, email: chk205@lehigh.edu

5 Procedures & Policies

This chapter describes the procedures and policies for use of the NHERI Lehigh RTMD EF. The experimental facility and its associated equipment is housed within the structural testing laboratory of the ATLSS Engineering Research Center. ATLSS's facilities, including the NHERI Lehigh RTMD EF, are available for both academic/sponsored laboratory research and external (industrial) testing and use. As the ATLSS Research Center's laboratory includes both NHERI equipment and non-NHERI equipment, it is the goal of the Center to accommodate concurrent use of the laboratory. For use of NHERI equipment, priority will be given to NHERI projects. For the purposes of this policy statement, NHERI projects are defined as projects receiving funding through the NSF for use of the NHERI equipment or projects that have received approval by the NHERI NCO for shared-use access. The NHERI Lehigh RTMD EF will be responsible for maintaining NHERI equipment, operating the equipment during the experiments, and providing basic training to collaborating researchers for use of the equipment.

NHERI Projects

As previously noted, NHERI projects are defined as projects receiving funding through the NSF for use of the NHERI equipment or projects that have received approval by the NCO for shared-use access. Equipment use fees are not applied to equipment maintained under the NHERI Lehigh RTMD EF Operations and Maintenance budget (equipment covered in Section 1.3, RTMD Equipment Specifications) when utilized during a NHERI project. Additionally, for NHERI projects, select services covered within the scope of the site's Operations and Maintenance Budget that are performed by EF personnel are covered by the NHERI Lehigh RTMD EF Operations and Maintenance budget. NHERI projects have the opportunity to utilize non-NHERI (ATLSS) equipment on a use-fees basis. Rate schedules are provided in Section 6.2, Rate Schedule for NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories for NHERI projects (note Section 6.3, Rate Schedule for Non-NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories covers the rate schedule for non-NHERI projects). Regarding services, Section 6.1, Scope of Services Covered by the NHERI Operations and Maintenance Budget, outlines both activities and services covered by Lehigh's NHERI RTMD EF Operations and Maintenance budget and those activities and services that are to be covered by the research project. ***In summary, a researcher interested in developing costs associated with utilizing NHERI Lehigh's RTMD EF for a NHERI project should reference Section 6.1 to understand the scope of services which are covered under the NHERI Lehigh RTMD EF Operations and Maintenance budget and Section 6.2 to understand the cost structure associated with equipment and personnel required for the NHERI project.***

Note that all projects that utilize Lehigh's ATLSS Structural Testing Laboratory, whether NHERI or non-NHERI, is subject to an overall project fee, as outlined in Section 6.2. The project fee will be applied to each project to cover the cost of maintaining ATLSS lab tools, miscellaneous equipment, and facilities, such as, but not limited to, hand tools, forklift, overhead crane, and hydraulic pumping systems that are non-NHERI equipment. The fee will be assessed to each project at the time the project enters the laboratory.

Finally, visiting researchers will be provided office space at the ATLSS Center for the duration of their project, and will have restricted access to the ATLSS Lab and Fritz Lab for NHERI project related activities.

Non-NHERI Projects

Non-NHERI projects are considered those projects which are not sponsored by the National Science Foundation and which are not approved for shared-use access by the NCO, or those projects which are funded privately by industry with no intent of conforming to the requirements established in the NHERI Facilities Users Guide. *Non-NHERI project laboratory services and activities are not covered, in any manner, under the NHERI Lehigh RTMD EF Operations and Maintenance Budget*. All laboratory activities are to be charged directly to the laboratory project. Additionally, equipment use fees for use of both NHERI and non-NHERI equipment are applied to these projects. Rates for use of this equipment are outlined in Section 6.3, Rate Schedule for Non-NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories. Note that each project is subject to an overall project fee, as outlined in Section 6.3, which is a function of the project's budget specific to utilization of the ATLSS Laboratory and is dependent on whether the project is Academic/Sponsored or External Testing and Use. The project fee will be applied to each project to cover the cost of maintaining ATLSS lab tools, miscellaneous equipment, and facilities, such as, but not limited to, hand tools, forklift, overhead crane and hydraulic pumping systems that are non-NHERI equipment. The fee will be assessed to each project upon entry of the project into the laboratory.

5.1 Guidelines for Proposal Preparation

Researchers interested in developing a proposal to utilize Lehigh's Equipment Site are referred to NHERI Facilities Users Guide, which can be downloaded directly from the Policies section on designsafe-ci.org. Lehigh's site also recommends that contact be made early in the proposal process with NHERI Lehigh's RTMD EF Operations Manager, in order to aid in planning, scheduling, cost development, etc. Lehigh also intends to offer an annual Seismic Testing Workshop through designsafe-ci.org with the goal of training potential site users on the site's capabilities, equipment specifications, proposal development, etc. Researchers interested in utilizing the equipment site are strongly encouraged to attend the workshop. The NHERI Lehigh RTMD EF Operations Manager contact information is as follows: Dr. Chad Kusko, NHERI Lehigh RTMD EF Operations Manager, phone 610-758-5299, email: chk205@lehigh.edu.

5.2 Guidelines for Funded Projects

Researchers that have received funding to utilize Lehigh's Equipment Site are referred to the NHERI Facilities Users Guide, which can be downloaded directly from the Policies section on designsafe-ci.org. This document includes a section entitled Guidelines for Funded Proposals. Among the topics covered in this section are Equipment Site Compliance Checks, Research Participation Agreements, and site scheduling. Researchers are strongly encouraged to review this section during the proposal development stage in order to understand the informational details that will be required by the equipment site upon funding of the project.

5.3 Required Documentation

As of the drafting of this document (4/1/16), there is no research participation agreement template or equipment site policies compliance check document required by NHERI. The NHERI Lehigh RTMD EF reserves the right to incorporate one, both, or a modification of the referenced documents prior to the onset of an awarded project at the RTMD EF. Check with the NHERI Lehigh RTMD EF Operations Manager regarding required documentation. Lehigh University reserves the right to deny the use of the RTMD EF to researchers for any reason if researcher actions are inconsistent with the goals and policies of the University.

For consideration of critical items in advance of potential NHERI projects, the following two primary documents ***were required for completion prior to*** *the onset of any laboratory activity for an awarded NEES research project from 2004 through 2014*. The documents are outlined below:

1. Equipment Site Policies Compliance Check (ESPCC): To be completed by an equipment site representative, *with supporting information provided by the researcher*. The ESPCC assured policy compliance with respect to NEES Facilities Users Guide, experimental feasibility, safety, budget, schedule, and available data services. A copy of the ESPCC form is available at the NEES.org, under Policies.
2. Research Participation Agreement (RPA): *To be completed by the researcher*, with assistance from the equipment site staff. The RPA represented a contract between the Equipment Site and NEEScomm, detailing (but not limited to) sections including:

- Indemnification
- Insurance
- Payment terms
- Termination terms
- Intellectual Property rights
- Publication rights
- Change order procedures
- Conflict resolution procedures
- Scope of Work
- Project Description
- Project Schedule and Required Equipment
- Risk Mitigation Plan
- Safety Plan
- Data Sharing and Archiving Plan

- Budget for site activities
- Roles and Responsibilities for both researcher and equipment site

5.4 Training

The NHERI Lehigh RTMD EF Training Plan intends to provide the level of information and training required for the following three user groups.

NHERI Proposers

NHERI proposers are researchers developing NHERI proposals that, if successful, would utilize the NHERI Lehigh RTMD EF. These researchers are expected to have basic understanding and some experience in laboratory experiments involving the dynamic effects of earthquakes on large structures and structural components. Two key components that provide the information required for NHERI proposers are the NHERI Facility User's Guide and material at designsafe-ci.org. These components together provide the information required to understand the physical facilities and test equipment and the procedures and policies to be followed at the NHERI Lehigh RTMD EF. A third component of proposer training is the offering of Seismic Testing Workshops by RTMD staff at the NHERI Lehigh facility. Additional information on such workshops is available through designsafe-ci.org. Further clarifications and budget development assistance will be available through the NHERI Lehigh RTMD Operations Manager.

NHERI On-Site Users

A formal on-site training program must be completed satisfactorily prior to any use of NHERI or non-NHERI equipment, including utilization of all ATLSS laboratory equipment. NHERI Lehigh RTMD EF staff will provide training through regularly scheduled training workshops for all RTMD facility users with awarded projects. For all projects, these training workshops will emphasize the safety procedures and policies described in the ATLSS Laboratory Safety Manual. An overview of the RTMD facility operations will also be provided. Additional training topics may include tasks specific to awarded projects, including instrumentation, data acquisition, control, and algorithm verification procedures. The duration of a training workshop will typically be one day and will be conducted at the RTMD facility. Any additional training required for a specific project should be discussed in the proposal preparation process and the costs included in the proposal and testing plan. This additional training may be conducted utilizing teleconferencing, if appropriate. The NHERI project PI and students and staff from the project PI's home institution and from any project subcontractors must be authorized by the NHERI Lehigh RTMD Operations Manager to have access to the ATLSS laboratory and any associated laboratory equipment. The staff of the NHERI Lehigh RTMD facility is available to assist and/or perform all functions related to the setup and operation of NHERI and non-NHERI equipment. All hydraulic actuators, hydraulic power systems, and control systems will be operated exclusively by NHERI Lehigh RTMD EF staff. These systems require extensive training and experience to operate properly. Improper operation poses significant risk to the facility and personnel in the ATLSS Lab. Additionally, trained members of the ATLSS staff will operate the ATLSS laboratory forklift, overhead crane and all other equipment requiring professional skill or operating certification.

NHERI Observers

The third component of the Training Plan is educational in its focus and is intended to enhance the understanding of the effects of seismic events on structures for practicing engineers, interested graduate and undergraduate students, and K-12 teachers and students. Project summaries for each research project will be developed and posted on designsafe-ci.org. It is the responsibility of the researcher to provide the NHERI Lehigh RTMD EF staff with the project summary and any additional information required by the NHERI Lehigh RTMD EF staff to post a project summary. Seminars may be conducted by the principal researcher or designate for each project. These seminars will be announced and open to the public.

5.5 Experiment Execution

Standard NHERI Lehigh RTMD EF and ATLSS laboratory hours of operation are 7:00 am to 12:00 pm, and 12:30 pm to 3:00 pm local time. Exceptions to this policy must be made in writing in advance and agreed upon by the NHERI Lehigh RTMD EF Operations Manager and ATLSS Laboratory Operations Manager. NHERI projects are responsible for overtime hours incurred by RTMD facility personnel during extended hours of operation. An exception to this policy may occur when extended hours of operation result from malfunction of the RTMD facility equipment. The NHERI Lehigh RTMD EF Director and staff recognize the importance of opening the facility to all members of the natural hazards infrastructure engineering community for their research needs. Efforts have been made to maintain a safe, secure working environment for participants and visitors. There are, however, some areas within the ATLSS laboratory that remain accessible only to NHERI Lehigh RTMD EF staff only. In general, these are consistent with standard safety practices and reflect a cautious approach in the interest of safety. As an example of such, the hydraulic pump house and electrical service equipment will remain closed to all visitors, including those working on NHERI projects.

ATLSS laboratory, which houses the NHERI Lehigh RTMD facility, is a ground level laboratory fully compliant with ADA requirements. Offices within and adjacent to the ATLSS laboratory are also accessible. Special accommodations may be arranged with advance notice. The ATLSS Engineering Center offers office spaces with Ethernet access for visiting NHERI project personnel. While the ATLSS laboratory does not operate on a 24-hour basis, the ATLSS Engineering Research Center is accessible at all hours, but requires after hours authorization for admittance.

The control room for the NHERI Lehigh RTMD facility has a window facing the ATLSS laboratory and is designed to accommodate up to 4 researchers with computer access available. As a safety precaution, during testing, researchers will be asked to refrain from entering the test area. The control room affords a limited view of the test area. Cameras focused on the test setup will provide more comprehensive views of the test. Video display screens will be available in the control room.

6 Cost Structure

NHERI projects do not pay for use of NHERI equipment or NHERI-funded personnel for qualified activities. The NHERI Lehigh RTMD EF will provide a baseline level of service to NHERI projects at no cost to the researcher. This cost will be absorbed by the NHERI Lehigh RTMD EF Operations and Maintenance budget. Section 6.1, Scope of Services Covered by the NHERI Operations and Maintenance Budget, provides a summary of these activities. Additional levels of service beyond those noted in Section 6.1 will be subject to user fees or will be chargeable directly to the research project.

Section 6.2, Rate Schedule for NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories, outlines the rate schedule for utilization of equipment for **NHERI projects only**. Section 6.3, Rate Schedule for Non-NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories, outlines the rate schedule for non-NHERI projects. Fees will be charged for the use of non-NHERI equipment by all projects and for the use of NHERI equipment by non-NHERI projects. The unit basis applied to all equipment to determine its use is also provided in Sections 6.2 and 6.3.

A project fee will be applied to all projects to cover the maintenance costs associated with ATLSS lab tools, miscellaneous equipment, and facilities, such as hand tools, forklift, overhead crane and hydraulic pumping systems that are non-NHERI equipment. The standard fee, which is determined as a specific percentage of the project budget specific to utilization of Lehigh's ATLSS Laboratory, is outlined in Sections 6.2 and 6.3 (note the information is similar as the tables are duplicate).

Additional charges will be applied according to the attached tables in Section 6.2 (for NHERI projects) and Section 6.3 (for non-NHERI projects). The space use charges are intended to help cover the cost of maintaining the ATLSS laboratory infrastructure, including, the strong floor and reaction walls. Other charges will allow recharging (e.g., for strain gages) or maintenance (e.g., non-NHERI actuators) of the respective equipment.

In addition, NHERI research projects are responsible for all fees and shipping costs from equipment and services provided by off-campus contractors. NHERI projects are responsible for all travel costs associated with the project. This includes lodging, per diem, airline fares, rental cars, mileage reimbursement and parking fees.

6.1 Scope of Services Covered by the NHERI Operations and Maintenance Budget

For NSF NHERI-related activities (including NSF NHERI research projects, training, maintenance, calibration, safety, education, and outreach activities), tasks conducted at the Lehigh EF could be the financial responsibility of either:

1. The NHERI Lehigh RTMD EF Operations and Maintenance budget (Table 6-1), or
2. The NSF sponsored NHERI research project (Table 6-2)

The tables below assign the responsibility of costs to either the Lehigh NHERI RTMD EF Operations and Maintenance budget or the NSF NHERI project budget.

When preparing a NSF NHERI research proposal, researchers are strongly encouraged to contact the NHERI Lehigh RTMD EF Operations Manager to review the project demands in order to most accurately develop a research project budget and to understand potential future impacts on the NHERI RTMD EF Lehigh Operations and Maintenance budget.

Table 6-1 Responsibility of NHERI Lehigh Operations and Maintenance Budget

Responsibility of NHERI Lehigh Operations and Maintenance Budget
Maintain all NHERI equipment and instrumentation at full function
Maintain fixtures related to NHERI equipment
Reconfiguration and operation of NHERI equipment, including DAQ system during NHERI- related activities
Operation of NHERI equipment and instrumentation during NHERI-related activities
Assist researchers with NHERI sensor/instrument calibration
All services associated with onsite NHERI-related training activities
Assist NHERI researchers with laboratory cost estimation
Assist NHERI researchers with proposal development (laboratory, equipment, and infrastructure)
Assist NHERI researchers with post-award planning and design (laboratory, equipment, and infrastructure)
Conduct training activities associated with equipment operation and safety
Provide safety and risk management for staff and visitors
Provide video conferencing support
Data transfer to NHERI data repository
Office space and Ethernet access
Liaison services with local contractors
Use of ATLSS ancillary equipment (such as fork lifts, cranes, saws, etc.)

Table 6-2 Responsibility of NSF NHERI Research Project Budget

Responsibility of NSF NHERI Research Project Budget
Assist researchers with sensor/instrument installation (for both NHERI and non-NHERI sensors/ instruments), including cable fabrication and connection of all cables from test specimen/fixture to DAQ
Construct test specimens, including receiving, fabrication, assembly, demolition, and disposal
Construct experiment-specific test fixtures (if existing fixtures are not suitable for the proposed test program), including labor and materials associated with receiving, fabrication, assembly, demolition, and disposal
Services and use fees associated with use of non-NHERI facilities, equipment, or instrumentation (including machining, welding, universal testing machines, non-NHERI actuators, non-NHERI instrumentation, etc.)
Time associated with purchases required to support specific research project
Acquisition of miscellaneous materials and supplies specific to the project, including consumables, special tools, wires and cables, strain gages, sensors not available at the NHERI Lehigh EF, and special sensor mounting devices.
Development of special instrumentation and data-acquisition capabilities that are not available at the NHERI Lehigh EF and modification of existing electronic systems and network
Materials testing
Use fees as outlined per Table 5.9 for NHERI research projects
Space use for receiving, assembly, and storage of fixtures and specimens

6.2 Rate Schedule for NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories

Table 6-10 through Table 6-8 apply to rates associated with **NHERI projects only**. NHERI projects are defined as projects receiving funding through the NSF for utilization of NHERI Lehigh RTMD Experimental Facility equipment. All other non-NHERI projects are subject to the rates in Section 6.3

Note: All costs in subsequent tables are direct cost only (personnel costs also include employee benefits as noted in Table 6-5). All costs will be subject to Lehigh University's current indirect cost rate. Contact NHERI Lehigh RTMD EF Operations Manager for university's current indirect cost rate. For use fees assessed per day, the charges will be applied in either half day or full day increments.

Table 6-3 ATLSS PROJECT FEE

ATLSS PROJECT FEE		
The ATLSS Project Fee is assessed as a *one-time* charge at the onset of a project at the percentages noted below. The fee is assessed *on the total test program* budget. The fee is assessed to cover costs associated with forklifts, cranes, hydraulic pumps, tools, etc. required for daily operation at ATLSS.		
	Unit of Measure	**NHERI Projects**
ATLSS Project Fee	Per project	1%

Table 6-4 FLOOR, WALL SPACE, and RED BRACING FRAME – ATLSS Laboratory

FLOOR, WALL SPACE, and RED BRACING FRAME – ATLSS Laboratory		
** Note: Floor space/wall space charge is applicable to strong floor/reaction wall in laboratory's south bay (excluding red bracing frame fixture which is explained below) and to the steel test frame/wall grillage system in laboratory's north bay.*		
Floor Space* (excludes floor space within red bracing frame fixture)		
Description	**Unit of Measure**	**NHERI Projects**
Floor Space < 500 sq ft	Per calendar day	$0
Floor Space to 1000 sq ft	Per calendar day	$50
Floor Space to 1500 sq ft	Per calendar day	$100
Floor Space to 2000 sq ft	Per calendar day	$150
Floor Space to 2500 sq ft	Per calendar day	$200
Floor Space to 3000 sq ft	Per calendar day	$250
Floor Space to 3500 sq ft	Per calendar day	$300

Floor Space to 4000 sq ft	Per calendar day	$400
Wall Space* (excludes wall space within red bracing frame fixture)		
Calculated by multiplying applicable floor space daily rate by wall space occupancy/blockage factor (provided below)		
Description	**Unit of Measure**	**NHERI Projects**
Wall space < 20 ft	-----	1.0
Wall space to 30 ft	-----	1.3
Wall space to 40 ft	-----	1.6
Wall space to 50 ft	-----	2.0
ATLSS Red Bracing Frame**		
ATLSS Bracing Frame Fixture**	Per project per calendar year	$15,000
*** Projects whose floor and/or wall plan footprint lie within the red bracing frame fixture are charged a $15,000 per project per calendar year usage fee in place of being charged per square foot for floor space and per foot for wall space for this area. Projects whose floor space footprint and wall space footprint fall outside of the red bracing frame but which utilize the outside of the red bracing frame as a support fixture are subject to the standard floor and wall space use fees as outlined above for projects whose footprint falls outside of the red bracing frame fixture.*		

Table 6-5 PERSONNEL - Labor

PERSONNEL - Labor		
Personnel costs could be the responsibility of the NHERI project or the NHERI Lehigh Operations and Maintenance budget depending on the associated task. The section entitled “Responsibility of Project Costs” should be reviewed for determination. The personnel costs in Table 5.9-3 below would be the rates applied for tasks that are the responsibility of the NHERI research project. **ATLSS Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)**		
Personnel	**Unit of Measure**	**NHERI Projects**
Manager, Structural Testing	Per hour	$82
Laboratory Operations Manager	Per hour	$47
Laboratory Technicians	Per hour	$43
Instrumentation Manager	Per hour	$63
Instrumentation Technicians	Per hour	$63
ATLSS IT Manager	Per hour	$66
Administrative Assistant	Per hour	$24
NHERI Lehigh RTMD EF Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)		
Personnel	**Unit of Measure**	**NHERI Projects**
NHERI Lehigh Operations Manager	Per hour	$103
NHERI Lehigh IT Systems Administrator	Per hour	$73

Table 6-6 NHERI EQUIPMENT/INSTRUMENTATION

NHERI EQUIPMENT/INSTRUMENTATION		
NHERI Equipment		
Description	**Unit of Measure**	**NHERI Projects**
NHERI Hydraulic System (NHERI actuators)	Setup per project per calendar year	$0
- Static per actuator	Per test day	$0
- Dynamic per actuator	Per test day	$0
- Fatigue to 5M per actuator	Per M cycles	$0
- Fatigue 5M–50M per actuator	Per M cycles	$0
- Fatigue 50M–200M per actuator	Per M cycles	$0
- Fatigue >200M per actuator	Per M cycles	$0
NHERI Accumulator System	Setup per project per calendar year	$0
- Accumulator discharge	Per discharge	$0
NHERI Control System (Pulsar or Inertia)	Setup per project per calendar year	$0
- NHERI Control System	Per test day	$0
Note 1: For NHERI projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate (based on cycle count) for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.		
Note 2: Fatigue projects (for NHERI projects) will not be subject to static test charges for setting load limits for fatigue tests if the loads in such tests do not exceed the fatigue test load range. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.		
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.		
Note 4: Equipment subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:		
- Weekly rate (>2 days/calendar week)		2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week
NHERI Instrumentation (*Charges per instrument, regardless of quantity*)		
Description	**Unit of Measure**	**NHERI Projects**
NHERI Data Acquisition System (Pacific Instruments)	Per test day	$0
NHERI Accelerometers (monoaxial)	Per test day	$0
NHERI Accelerometers (triaxial)	Per test day	$0
NHERI Temposonics	Per test day	$0
NHERI LVDTs	Per test day	$0
NHERI Inclinometers	Per test day	$0
NHERI Differential Pressure Transducers	Per test day	$0

Camera	Setup per camera per project	$0
- Portable Web Camera	Per test day	$0
- GoPro Camera	Per test day	$0
Agilent Power Supply	Per instrument	$0
Agilent Volt Meter	Per instrument	$0
Note: Instrumentation subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:		
- Weekly rate (>2 days/calendar week)		2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week

Table 6-7 Non-NHERI EQUIPMENT/ INSTRUMENTATION

Non-NHERI EQUIPMENT/ INSTRUMENTATION		
ATLSS LABORATORY		
Non-NHERI Equipment		
Description	**Unit of Measure**	**NHERI Projects**
ATLSS Hydraulic System (non-NHERI actuators)	Setup per project per year	$250
- Static per actuator*	Per test day	$150
- Dynamic per actuator*	Per test day	$250
- Fatigue to 5M per actuator	Per M cycles	$162
- Fatigue 5M–50M per actuator	Per M cycles	$100
- Fatigue 50M–200M per actuator	Per M cycles	$50
- Fatigue >200M per actuator	Per M cycles	$20
Enerpac Pumping System	Per test day	$0
Enerpac Jacks	Per test day	$0
Manlift	Per test day	$0
ATLSS Control System	Setup per project per calendar year	$50
- MTS Flex System*	Per channel per test day	$20
- MTS 458 System*	Per channel per test day	$12
- Wineman System*	Per channel per test day	$12
- Vickers System (includes conditioner)*	Per channel per test day	$10

Note 1: For NHERI projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.	
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.	
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.	
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:	
- Weekly rate (>2 days/calendar week)	2.5*day
- Monthly rate (>2 weeks/calendar month)	2.5*week

Non-NHERI Instrumentation (*Charges dependent on quantity of instrumentation utilized*)		
Description	**Unit of Measure**	**NHERI Projects**
Trilion 3-D Image Correlation System	-----	-----
- Static	Per test day (not subject to weekly and monthly rates)	$285
- Dynamic	Per test day (not subject to weekly and monthly rates)	$570
DaqScribe High Speed Data Acquisition System	Per test day (not subject to weekly and monthly rates)	$125
Data Acquisition System	-----	-----
- To 16 channels*	Per test day	$38
- 17 – 32 channels*	Per test day	$75
- 33 – 64 channels*	Per test day	$100
- 65 – 96 channels*	Per test day	$125
- >96 channels*	Per test day	$150
- CR9000 data logger (includes power supply charge)*	Per test day	$81
- CR5000 data logger (includes power supply charge)*	Per test day	$56
- Daytronics*	Per test day	$25
Strain gage conditioners	Per test day	-----

- 1 – 8 channels*	Per test day	$5
- 9 – 16 channels*	Per test day	$10
- 17 – 32 channels*	Per test day	$20
- 33 – 64 channels*	Per test day	$30
- > 64 channels*	Per test day	$40
Strain Indicator	Per test day	$5
Peak Reader	Per test day	$5
Precision Voltmeter	Per test day	$10
Power Supply	Per test day	$0
LVDTs, Temposonics, Displacement Transducers	-----	-----
- 1 – 8*	Per test day	$10
- 9 – 16*	Per test day	$15
- 17 – 24*	Per test day	$20
- 25 – 32*	Per test day	$25
- 33 – 40*	Per test day	$30
- 41 – 48*	Per test day	$35
- 49 – 56*	Per test day	$40
- 57 – 64*	Per test day	$45
- > 64*	Per test day	$50
Plastic slides	-----	-----
- 1 – 8*	Per test day	$5
- 9 – 16*	Per test day	$10
- > 16*	Per test day	$15
String Pots, Accelerometers	-----	-----
- 1 – 4*	Per test day	$10
- 5 – 8*	Per test day	$15
- 9 – 12*	Per test day	$20
- > 12*	Per test day	$25
Rotation Meters, Inclinometers	-----	-----
- 1 – 8*	Per test day	$10
- 9 – 16*	Per test day	$15
- > 16*	Per test day	$20
Laser Displacement Sensors*	Per test day	$15
Load Cell*	Per test day	$10
Calibration stand*	Per test day	$8
Camera	Setup per camera per project	$15
Nikon Camera*	Per test day	$10
Videocam*	Per test day	$5
DVR*	Per test day	$5
Note: Instrumentation followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:		
- Weekly rate (>2 days/calendar week)		2.5*day

- Monthly rate (>2 weeks/calendar month)		2.5*week
FRITZ LABORATORY		
Non-NHERI Equipment		
Amsler Hydraulic System	Setup per project per year	$125
- Static per actuator*	Per test day	$75
- Fatigue to 5M per actuator	Per M cycles	$75
- Fatigue 5M–50M per actuator	Per M cycles	$50
- Fatigue 50M–200M per actuator	Per M cycles	$25
- Fatigue >200M per actuator	Per M cycles	$10
MTS/Vickers Hydraulic	Setup per project per year	$250
- Static per actuator*	Per test day	$150
- Fatigue to 5M per actuator	Per M cycles	$150
- Fatigue 5M–50M per actuator	Per M cycles	$100
- Fatigue 50M–200M per actuator	Per M cycles	$50
- Fatigue >200M per actuator	Per M cycles	$20
Amsler Alternating Stress Machine	Per M cycles	$75
Baldwin 5000 kip Universal*	Per test day	$250
Baldwin 5000 kip Universal*	Overnight	$100
Riehle 800 kip Universal*	Per test day	$150
Southwark Emery 300 kip Universal*	Per test day	$75
Drop Weight Tester	Per test day	$15
Rexroth Pumping System	Per test day	$100
Note 1: For NHERI projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.		
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.		
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.		
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:		
- Weekly rate (>2 days/calendar week)		2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week

Table 6-8 ADDITIONAL LABORATORIES/SERVICES/EQUIPMENT

ADDITIONAL LABORATORIES/SERVICES/EQUIPMENT		
ATLSS LABORATORY		
Description	**Unit of Measure**	**NHERI Projects**
Large Scale Furnace	Per test day	$50
Materials Testing	-----	-----
- Welding equipment	Per hour	$5
- Heat treating furnace	Per hour	$10
Mechanical Testing	-----	-----
- 2670 kN (600 kip) Universal	Per test day	$200
- 267 kN (60 kip) Universal	Per test day	$50
245 kN Servo	-----	-----
- Static	Per hour	$10
- < 5 M cycles	Per M cycles	$25
- 5 – 50 M cycles	Per M cycles	$25
- > 50 M cycles	Per M cycles	$10
Charpy V-notch Test Machine	Per test day	$50
Metallography Laboratory	-----	-----
- Sample preparation	Per sample	$5
- Hardness: Rockwell and Vickers	Per hour	$10
- Optical microscope	Per hour	$10

Additional Notes:

1. The testing machines at Fritz Laboratory are also available for use by NHERI researchers. Use fees estimates and associated costs will be developed on a per test basis, based on the complexity of the test setup. The Manager, Structural Testing will assist in developing estimates for the use of this machine.
2. All costs require indirect cost to be applied to the stated rates (stated rates are only direct cost, with the exception of personnel which also includes employee benefits). Contact the NHERI Lehigh RTMD EF Operations Manager for current Lehigh University indirect cost rates.
3. Space rates (both floor and wall) are applicable for total calendar days associated with a given project. Such rates are not subject to the special weekly and monthly rates noted above for select equipment and instrumentation.

6.3 Rate Schedule for Non-NHERI Projects for NHERI Lehigh RTMD Experimental Facility, ATLSS and Fritz Structural Testing Laboratories

Table 6-9 through Table 6-14 apply to rates associated with **non-NHERI projects only** (NSF funded projects that utilize the NHERI Lehigh RTMD EF are referred to in Section 6.2 for applicable costs). NHERI projects are defined as projects receiving funding through the NSF for utilization of NHERI Lehigh RTMD EF equipment. Non-NHERI projects are projects that do not qualify per the definition above.

Note: All costs in subsequent tables are direct cost only (personnel costs also include employee benefits as noted in Table 6-11). All costs will be subject to Lehigh University's current indirect cost rate. Contact NHERI Lehigh RTMD EF Operations Manager for university's current indirect cost rate. For use fees assessed per day, the charges will be applied in either half day or full day increments.

Table 6-9 ATLSS PROJECT FEE

ATLSS PROJECT FEE			
The ATLSS Project Fee is assessed as a *one-time* charge at the onset of a project at the percentages noted below. The fee is assessed *on the total test program* budget. The fee is assessed to cover costs associated with forklifts, cranes, hydraulic pumps, tools, etc. required for daily operation at ATLSS.			
	Unit of Measure	**Academic/ Sponsored**	**External Testing & Use**
ATLSS Project Fee	Per project	1%	2%

Table 6-10 FLOOR, WALL SPACE, and RED BRACING FRAME – ATLSS Laboratory

FLOOR, WALL SPACE, and RED BRACING FRAME – ATLSS Laboratory			
** Note: Floor space/wall space charge is applicable to strong floor/reaction wall in laboratory's south bay (excluding red bracing frame fixture which is explained below) and to the steel test frame/wall grillage system in laboratory's north bay.*			
Floor Space* (excludes floor space within red bracing frame fixture)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Floor Space < 500 sq ft	Per calendar day	$0	$50
Floor Space to 1000 sq ft	Per calendar day	$50	$100
Floor Space to 1500 sq ft	Per calendar day	$100	$200
Floor Space to 2000 sq ft	Per calendar day	$150	$300
Floor Space to 2500 sq ft	Per calendar day	$200	$400
Floor Space to 3000 sq ft	Per calendar day	$250	$500

Floor Space to 3500 sq ft	Per calendar day	$300	$600
Floor Space to 4000 sq ft	Per calendar day	$400	$800
Wall Space* (excludes wall space within red bracing frame fixture)			
Calculated by multiplying applicable floor space daily rate by wall space occupancy/blockage factor (provided below)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Wall space < 20 ft	-----	1.0	1.0
Wall space to 30 ft	-----	1.3	1.3
Wall space to 40 ft	-----	1.6	1.6
Wall space to 50 ft	-----	2.0	2.0
ATLSS Red Bracing Frame**			
ATLSS Bracing Frame Fixture**	Per project per calendar year	$15,000	$15,000

*** Projects whose floor and/or wall plan footprint lie within the red bracing frame fixture are charged a $15,000 per project per calendar year usage fee in place of being charged per square foot for floor space and per foot for wall space for this area. Projects whose floor space footprint and wall space footprint fall outside of the red bracing frame but which utilize the outside of the red bracing frame as a support fixture are subject to the standard floor and wall space use fees as outlined above for projects whose footprint falls outside of the red bracing frame fixture.*

Table 6-11 PERSONNEL - Labor

PERSONNEL - Labor			
ATLSS Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)			
Personnel	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Manager, Structural Testing	Per hour	$82	$83
Laboratory Operations Manager	Per hour	$47	$48
Laboratory Technicians	Per hour	$43	$47
Instrumentation Manager	Per hour	$63	$64
Instrumentation Technicians	Per hour	$63	$64
ATLSS IT Manager	Per hour	$66	$67
Administrative Assistant	Per hour	$24	$25
NHERI Lehigh RTMD EF Staff (rates include vacation, holiday, and sick leave and employee benefits but does not include indirect cost)			
Personnel	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NHERI Lehigh Operations Manager	Per hour	$103	$104
NHERI Lehigh IT Systems Administrator	Per hour	$73	$74

Table 6-12 NHERI EQUIPMENT/INSTRUMENTATION

NHERI EQUIPMENT/INSTRUMENTATION			
NHERI Equipment			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NHERI Hydraulic System (NHERI actuators)	Setup per project per calendar year	$250	$1000
- Static per actuator	Per test day	$200	$800
- Dynamic per actuator	Per test day	$300	$1200
- Fatigue to 5M per actuator	Per M cycles	$200	$800
- Fatigue 5M–50M per actuator	Per M cycles	$150	$600
- Fatigue 50M–200M per actuator	Per M cycles	$100	$400
- Fatigue >200M per actuator	Per M cycles	$50	$200
NHERI Accumulator System	Setup per project per calendar year	$150	$600
- Accumulator discharge	Per discharge	$100	$400
NHERI Control System (Pulsar or Inertia)	Setup per project per calendar year	$200	$600
- NHERI Control System	Per test day	$150	$600
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate (based on cycle count) for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects (both Academic/Sponsored and External Use & Testing) will not be subject to static test charges for setting load limits for fatigue tests if the loads in such tests do not exceed the fatigue test load range. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week
NHERI Instrumentation (*Charges per instrument, regardless of quantity*)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
NHERI Data Acquisition System (Pacific Instruments)	Per test day	$150	$600
NHERI Accelerometers (monoaxial)	Per test day	$15	$60
NHERI Accelerometers (triaxial)	Per test day	$20	$80

NHERI Temposonics	Per test day	$15	$60
NHERI LVDTs	Per test day	$10	$40
NHERI Inclinometers	Per test day	$15	$60
NHERI Differential Pressure Transducers	Per test day	$15	$60
Camera	Setup per camera per project	$15	$60
- Portable Web Camera	Per test day	$10	$40
- GoPro Camera	Per test day	$20	$80
Agilent Power Supply	Per instrument	$10	$40
Agilent Volt Meter	Per instrument	$15	$60
Note: Instrumentation subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week

Table 6-13 Non-NHERI EQUIPMENT/ INSTRUMENTATION

Non-NHERI EQUIPMENT/ INSTRUMENTATION			
ATLSS LABORATORY			
Non-NHERI Equipment			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
ATLSS Hydraulic System (non-NHERI actuators)	Setup per project per year	$250	$1000
- Static per actuator*	Per test day	$150	$600
- Dynamic per actuator*	Per test day	$250	$1000
- Fatigue to 5M per actuator	Per M cycles	$162	$650
- Fatigue 5M–50M per actuator	Per M cycles	$100	$400
- Fatigue 50M–200M per actuator	Per M cycles	$50	$200
- Fatigue >200M per actuator	Per M cycles	$20	$80
Enerpac Pumping System	Per test day	$0	$0
Enerpac Jacks	Per test day	$0	$0
Manlift	Per test day	$0	$0
ATLSS Control System	Setup per project per calendar year	$50	$200
- MTS Flex System*	Per channel per test day	$20	$70
- MTS 458 System*	Per channel per test day	$12	$45

- Wineman System*	Per channel per test day	$12	$45
- Vickers System (includes conditioner)*	Per channel per test day	$10	$40
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			
Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week

Non-NHERI Instrumentation (*Charges dependent on quantity of instrumentation utilized*)			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Trilion 3-D Image Correlation System	-----	-----	-----
- Static	Per test day (not subject to weekly and monthly rates)	$285	$1140
- Dynamic	Per test day (not subject to weekly and monthly rates)	$570	$2280
DaqScribe High Speed Data Acquisition System	Per test day (not subject to weekly and monthly rates)	$125	$500
Data Acquisition System	-----	-----	-----
- To 16 channels*	Per test day	$38	$150
- 17 – 32 channels*	Per test day	$75	$300
- 33 – 64 channels*	Per test day	$100	$400
- 65 – 96 channels*	Per test day	$125	$500
- >96 channels*	Per test day	$150	$600
- CR9000 data logger (includes power supply charge)*	Per test day	$81	$325

- CR5000 data logger (includes power supply charge)*	Per test day	$56	$225
- Daytronics*	Per test day	$25	$100
Strain gage conditioners	Per test day	-----	-----
- 1 – 8 channels*	Per test day	$5	$20
- 9 – 16 channels*	Per test day	$10	$40
- 17 – 32 channels*	Per test day	$20	$80
- 33 – 64 channels*	Per test day	$30	$120
- > 64 channels*	Per test day	$40	$160
Strain Indicator	Per test day	$5	$20
Peak Reader	Per test day	$5	$20
Precision Voltmeter	Per test day	$10	$30
Power Supply	Per test day	$0	$0
LVDTs, Temposonics, Displacement Transducers	-----	-----	-----
- 1 – 8*	Per test day	$10	$40
- 9 – 16*	Per test day	$15	$60
- 17 – 24*	Per test day	$20	$80
- 25 – 32*	Per test day	$25	$100
- 33 – 40*	Per test day	$30	$120
- 41 – 48*	Per test day	$35	$140
- 49 – 56*	Per test day	$40	$160
- 57 – 64*	Per test day	$45	$180
- > 64*	Per test day	$50	$200
Plastic slides	-----	-----	-----
- 1 – 8*	Per test day	$5	$20
- 9 – 16*	Per test day	$10	$40
- > 16*	Per test day	$15	$60
String Pots, Accelerometers	-----	-----	-----
- 1 – 4*	Per test day	$10	$40
- 5 – 8*	Per test day	$15	$60
- 9 – 12*	Per test day	$20	$80
- > 12*	Per test day	$25	$100
Rotation Meters, Inclinometers	-----	-----	-----
- 1 – 8*	Per test day	$10	$40
- 9 – 16*	Per test day	$15	$60
- > 16*	Per test day	$20	$80
Laser Displacement Sensors*	Per test day	$15	$60
Load Cell*	Per test day	$10	$40
Calibration stand*	Per test day	$8	$30
Camera	Setup per camera per project	$15	$60
Nikon Camera*	Per test day	$10	$40
Videocam*	Per test day	$5	$20

DVR*	Per test day	$5	$20
Note: Instrumentation followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:			
- Weekly rate (>2 days/calendar week)		2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)		2.5*week	2.5*week
FRITZ LABORATORY			
Non-NHERI Equipment			
Amsler Hydraulic System	Setup per project per year	$125	$500
- Static per actuator*	Per test day	$75	$300
- Fatigue to 5M per actuator	Per M cycles	$75	$300
- Fatigue 5M–50M per actuator	Per M cycles	$50	$200
- Fatigue 50M–200M per actuator	Per M cycles	$25	$100
- Fatigue >200M per actuator	Per M cycles	$10	$40
MTS/Vickers Hydraulic	Setup per project per year	$250	$1000
- Static per actuator*	Per test day	$150	$600
- Fatigue to 5M per actuator	Per M cycles	$150	$600
- Fatigue 5M–50M per actuator	Per M cycles	$100	$400
- Fatigue 50M–200M per actuator	Per M cycles	$50	$200
- Fatigue >200M per actuator	Per M cycles	$20	$80
Amsler Alternating Stress Machine	Per M cycles	$75	$300
Baldwin 5000 kip Universal*	Per test day	$250	$1000
Baldwin 5000 kip Universal*	Overnight	$100	$400
Riehle 800 kip Universal*	Per test day	$150	$600
Southwark Emery 300 kip Universal*	Per test day	$75	$300
Drop Weight Tester	Per test day	$15	$60
Rexroth Pumping System	Per test day	$100	$400
Note 1: For Academic/Sponsored projects with actuator use subject to fatigue use rates above, the number of cycles used in determining the applicable use rate for *all actuators* on that project is calculated by summing the number of cycles run for all actuators.			
Note 2: Fatigue projects will not be subject to static test charges for setting load limits for fatigue tests if the loads are not exceeding the fatigue test ranges. If these conditions are met, the tests conducted at slow rate to establish the load limits for cycling do not qualify as static tests. If fatigue test ranges are exceeding, then static test charges are applicable to the project.			
Note 3: Crawl tests conducted on bridge fatigue simulation projects are subject to static test rates for actuators utilized during testing.			

Note 4: Equipment followed by * subject to weekly and monthly rates (as opposed to the per day rate noted above) if the following criteria are met:		
- Weekly rate (>2 days/calendar week)	2.5*day	2.5*day
- Monthly rate (>2 weeks/calendar month)	2.5*week	2.5*week

Table 6-14 ADDITIONAL LABORATORIES/SERVICES/EQUIPMENT

ADDITIONAL LABORATORIES/SERVICES/EQUIPMENT			
ATLSS LABORATORY			
Description	**Unit of Measure**	**Academic/ Sponsored**	**External Testing & Use**
Large Scale Furnace	Per test day	$50	$200
Materials Testing	-----	-----	-----
- Welding equipment	Per hour	$5	$10
- Heat treating furnace	Per hour	$10	$20
Mechanical Testing	-----	-----	-----
- 2670 kN (600 kip) Universal	Per test day	$200	$400
- 267 kN (60 kip) Universal	Per test day	$50	$100
245 kN Servo	-----	-----	-----
- Static	Per hour	$10	$15
- < 5 M cycles	Per M cycles	$25	$75
- 5 – 50 M cycles	Per M cycles	$25	$35
- > 50 M cycles	Per M cycles	$10	$15
Charpy V-notch Test Machine	Per test day	$50	$100
Metallography Laboratory	-----	-----	-----
- Sample preparation	Per sample	$5	$10
- Hardness: Rockwell and Vickers	Per hour	$10	$15
- Optical microscope	Per hour	$10	$15

Additional Notes:

1. The testing machines at Fritz Laboratory are also available for use by NHERI researchers. Use fees estimates and associated costs will be developed on a per test basis, based on the complexity of the test setup. The Manager of Structural Testing will assist in developing estimates for the use of this machine.
2. All costs require indirect cost to be applied to the stated rates (stated rates are only direct cost, with the exception of personnel which also includes employee benefits). Contact the NHERI Lehigh RTMD EF Operations Manager for current Lehigh University indirect cost rates.

3. Space rates (both floor and wall) are applicable for total calendar days associated with a given project. Such rates are not subject to the special weekly and monthly rates noted above for select equipment and instrumentation.

7 Facility Organization

This chapter describes the staff organization and capabilities of the NHERI Lehigh RTMD EF at Lehigh University.

7.1 Overview

The NHERI Lehigh RTMD EF is not a stand-alone facility, but rather a component of the existing ATLSS Engineering Research Center at Lehigh University. All NHERI experiments are expected to require the utilization of both ATLSS and RTMD facility components. The ATLSS Engineering Research Center consists of the strong floor/reaction wall/hydraulic pump system/multi-directional laboratory that are utilized by the RTMD facility. The RTMD facility adds a significant enhancement to the ATLSS hydraulic system capability through the installation of the 3030 liters (800 gallons), 24 MPa (3500 psi) hydraulic oil accumulator, and the high load rate actuators and servo-valves. Additional enhancements include servo-hydraulic controllers and the high speed data acquisition system. All of these components are described in detail in Section 1 of this manual. Thus, the RTMD facility and ATLSS lab share many common components, not all of which were funded by the NSF NHERI Program. Similarly, the RTMD EF staff is also a component of the ATLSS Engineering Research Center. Depending on the specific staff position, there may be associated responsibilities for solely the NHERI Lehigh RTMD EF or both the EF and the ATLSS Engineering Research Center operation. NHERI operation and maintenance (O&M) funding reflects this overlap for both staff and facilities. The costs associated with EF staff and facility maintenance are funded through the NHERI Lehigh RTMD Operations and Maintenance budget, while similar costs for non-NHERI activities are funded by non-NHERI sources. Thus, NHERI projects may be required to cover a portion of the costs of both the staff and the facility maintenance if project costs exceed the Operations and Maintenance funding allocation for NHERI projects.

As an example of this functional overlap for the staff, the ATLSS Laboratory Operations Manager is responsible for overseeing the laboratory activities associated with all testing conducted in the ATLSS laboratory, including both NHERI and non-NHERI test programs. The ATLSS Laboratory Operations Manager position is only partially funded by the NHERI Lehigh RTMD EF Operations and Maintenance budget. This is similar for additional NHERI Lehigh RTMD EF personnel, with the exception of the NHERI Lehigh IT Manager and NHERI Lehigh Research Engineer positions, which are funded solely through the NHERI Lehigh RTMD EF Operations and Maintenance budget.

Following are listings of the key personnel at both the NHERI Lehigh RTMD EF and ATLSS Enginering Research Center, along with contact information. Groupings are according to the primary source of support.

7.2 NHERI Lehigh RTMD EF Organization

Principal Investigator	James M. Ricles, Ph.D., P.E. (jmr5@lehigh.edu)
Co-Principal Investigator	Richard Sause, Ph.D., P.E. (rs0c@lehigh.edu)
Operations Manager	Chad S. Kusko, Ph.D. (chk205@lehigh.edu)
IT Manager	Thomas M. Marullo (tmm3@lehigh.edu)

7.3 ATLSS Organization

Director	Richard Sause, Ph.D. (rs0c@lehigh.edu)
Deputy Director	James M. Ricles, Ph.D. (jmr5@lehigh.edu)
Administrative Director	Chad S. Kusko, Ph.D. (chk205@lehigh.edu)
Administrative Assistant	Leila Mazarul (lem415@lehigh.edu)
Accounts Manager	Doris Oravec (dao1@lehigh.edu)
Manager Structural Testing	Ian Hodgson (ich2@lehigh.edu)
Laboratory Operations Manager	Darrick Fritchman (djf310@lehigh.edu)
Instrumentation Manager	Edward A. Tomlinson (eat2@lehigh.edu)
Instrumentation Manager	Carl Bowman (cab6@lehigh.edu)
Materials Program Manager	
Infrastructure Monitoring Program Manager	Richard Sause, Ph.D., P.E. (rs0c@lehigh.edu)
IT Systems Manager	Peter Bryan (pb02@lehigh.edu)
Web Developer	Peter Bryan (pb02@lehigh.edu)

7.4 ATLSS Research Center Facilities

The following describes the resources available to NHERI researchers at the NHERI Lehigh RTMD EF within the ATLSS Engineering Research Center.

7.4.1 Laboratory Technician Staff

The ATLSS Engineering Research Center maintains a staff of laboratory technicians to support the setup and removal of large scale experiments and to maintain the hydraulic supply system and reaction wall facility. These technicians operate all of the lab mobile equipment, including forklifts and overhead cranes, for all functions. They also have the capability to form and pour concrete and fabricate reinforcing. They are skilled in steel fabrication and erection with significant experience in layout, fitting, burning welding, heat straightening and erection of both fixtures and specimens. Additional capabilities include hydraulic systems operation and maintenance. This technician staff works under the direction of the ATLSS Laboratory Operations Manager.

7.4.2 Instrumentation Support Staff

The ATLSS Engineering Research Center maintains a staff of instrumentation support personnel to support the data acquisition and control functions for all experiments. Their functions include the maintenance and setup of the data acquisition and control system computers, the installation of all instrumentation as required by individual experiments, and the maintenance of all electronic equipment required for large scale experimentation. This staff has been trained in the use of the NHERI equipment, including the Pacific Instruments data acquisition system, Wineman servo controller system and the Servotest servo controller system. They are experienced in the application of all instrumentation used in structural experiments involving concrete, steel, fiber reinforced polymers, and composite materials. The instrumentation support staff work in conjunction with the ATLSS Laboratory Operations Manager.

7.4.3 ATLSS Structural Testing Laboratory

This laboratory accommodates both small scale and full size test structures composed of all materials, facilitated by a test floor measuring 40' by 102', and fixed reaction walls up to 50' high encircling three corners of the test floor. Multidirectional loads and motions can be applied allowing the study of the behavior of complete structures under a wide variety of load conditions.

Contact: Ian Hodgson, ich2@lehigh.edu, 610-758-6105

7.4.4 Fritz Engineering Lab

Features 800,000 lb and 5,000,000 lb universal testing machines, and a dynamic test bed with broad fatigue-testing capabilities, and a wide range of instrumentation. Founded in 1909 and enlarged to the present capacity in 1954. Designated as an ASCE Civil Engineering Landmark Structure.

Contact: Robin Hendricks, rjh208@lehigh.edu, 610-758-3497

7.4.5 Mechanical Testing Laboratory

Capable of standard mechanical property tests of metallic, cementitious and composite construction materials. Features 60,000 lb. and 600,000 lb. universal testing machines, and Charpy V-Notch fracture toughness testing machine.

Contact: Ian Hodgson, ich2@lehigh.edu, 610-758-6105

7.4.6 Robert E. Stout Welding and Heat Treating Laboratory

The Robert D. Stout Welding and Joining Laboratory is equipped to produce test weldments by the shielded-metal-arc, gas-metal-arc, gas-tungsten-arc, and submerged-arc processes under accurately controlled parameters of voltage, current, and travel speed. In addition, the laboratory has facilities for preparing specimens by sawing and flame-cutting and by heating and quenching for various tests that include slow-notch-bend, hardenability, fracture-toughness, weld-restraint-cracking, implant, tension, and creep-rupture testing.

Contact: Dr. Chad Kusko, chk205@lehigh.edu, 610-758-5299

7.4.7 Metallography and Microscopy Laboratories

This facility is equipped for metallographic sample preparation and material characterization by light optical and electron microscopy techniques with hardness and micro hardness capabilities. The facility features SEM and Light Microscopy equipment.

Contact: Dr. Chad Kusko, chk205@lehigh.edu, 610-758-5299

7.4.8 Computational Laboratory for Life-Cycle Structural Engineering

This facility is equipped with several high performance computer desktops providing a large number of advanced Life-Cycle, Reliability, Risk, Optimization, and Structural Engineering software applications. These applications are also available on the Laboratory's 64-bit quad core computational server, which is capable of speedily performing heavy-duty computational tasks.

Contact: Dr. Dan M. Frangopol, dmf206@lehigh.edu, 610-758-6103

7.4.9 Laboratory of Advanced Integrated Technology for Intelligent Structures (LAITIS)

The Laboratory of Advanced Integrated Technology for Intelligent Structures (LAITIS) is focused on research and education in the areas of wireless sensor networks, structural health monitoring, advanced information technology for enhancement of civil infrastructure performance, structural dynamics and vibration. The lab is equipped with state-of-the-art vibration testing, sensor networks development and calibration equipment. In addition, the lab has a small-scale shaking table (18"x18"), which is used to simulate dynamic response of civil structures and prototype testbed experiments.

Contact: Dr. Shamim N. Pakzad, snp208@lehigh.edu, 610-758-3566

7.4.10 Nondestructive Evaluation (NDE) Laboratory

The Nondestructive Evaluation Laboratory is equipped to perform basic laboratory and field evaluation work on steel and concrete materials and structures. The laboratory also includes a variety of electronic hardware for bench top testing including oscilloscopes, function generators and filters. The laboratory is for both undergraduate and graduate research, and undergraduate instruction.

Contact: Dr. Stephen Pessiki, spp1@lehigh.edu, 610-758-3494

7.4.11 ATLSS Infrastructure Monitoring Program Vehicle

The vehicle is used to increase the productivity and the safety of those involved with the Infrastructure Monitoring Program. The vehicle provides space for storing and transporting equipment, and for working in the field.

Contact: Ian Hodgson, ich2@lehigh.edu, 610-758-6105